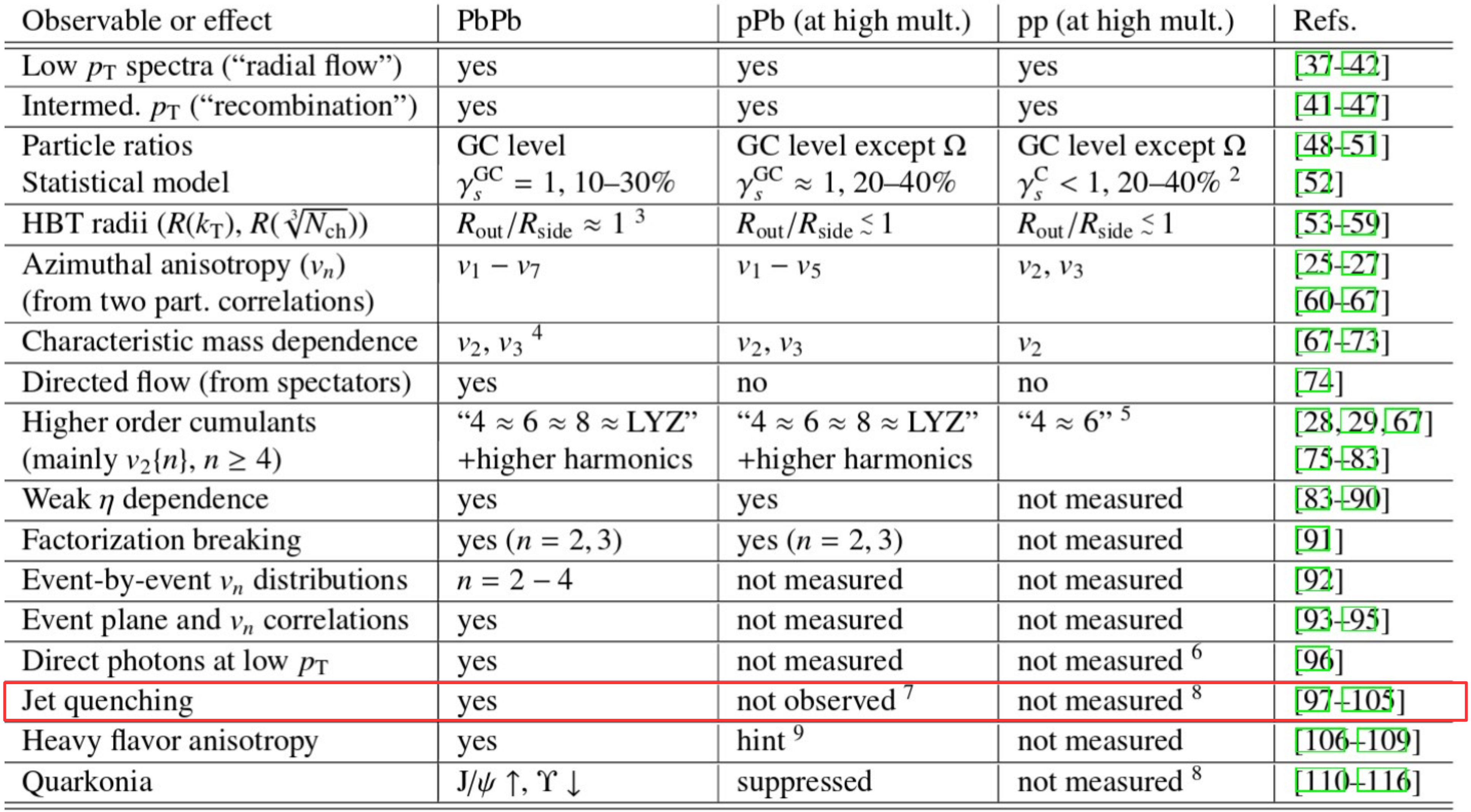
Parton energy loss: From pp(pA) to AA

C.Loizides (ORNL)
02 Nov 2017

Summary of typical HI observables

CL., arXiv:1602.09138



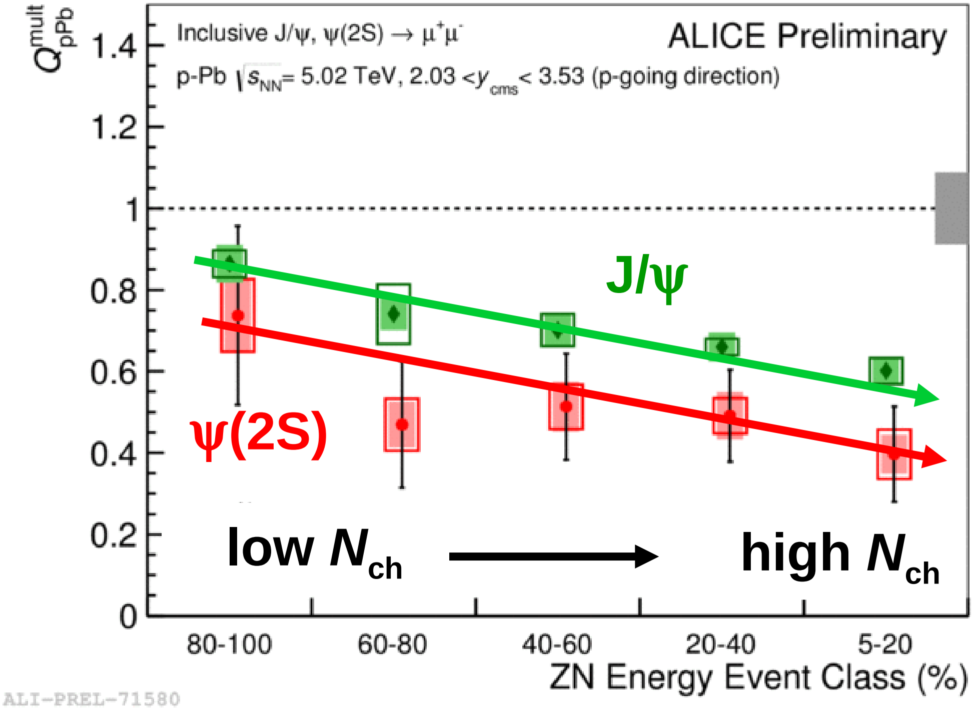
Observable or effect	PbPb	pPb (at high mult.)	pp (at high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[37–42]
Intermed. p_T ("recombination")	yes	yes	yes	[41–47]
Particle ratios Statistical model	GC level $\gamma_s^{GC} = 1$, 10–30%	GC level except Ω $\gamma_s^{GC} \approx 1$, 20–40%	GC level except Ω $\gamma_s^{C} < 1$, 20–40% [2]	[48–51] [52]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$ [3]	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[53–59]
Azimuthal anisotropy (v_n) (from two part. correlations)	$v_1 - v_7$	$v_1 - v_5$	v_2, v_3	[25–27] [60–67]
Characteristic mass dependence	v_2, v_3 [4]	v_2, v_3	v_2	[67–73]
Directed flow (from spectators)	yes	no	no	[74]
Higher order cumulants (mainly $v_2\{n\}, n \geq 4$)	"4 ≈ 6 ≈ 8 ≈ LYZ" +higher harmonics	"4 ≈ 6 ≈ 8 ≈ LYZ" +higher harmonics	"4 ≈ 6" [5]	[28, 29, 67] [75–83]
Weak η dependence	yes	yes	not measured	[83–90]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[91]
Event-by-event v_n distributions	$n = 2 - 4$	not measured	not measured	[92]
Event plane and v_n correlations	yes	not measured	not measured	[93–95]
Direct photons at low p_T	yes	not measured	not measured [6]	[96]
Jet quenching	yes	not observed [7]	not measured [8]	[97–105]
Heavy flavor anisotropy	yes	hint [9]	not measured	[106–109]
Quarkonia	J/ψ ↑, ϒ ↓	suppressed	not measured [8]	[110–116]

Observations qualitatively similar across systems for similar multiplicity, and can be reconciled by postulating a sQGP, even in high mult pp collisions. But no direct evidence for parton energy loss, which - even if tiny - should be there!

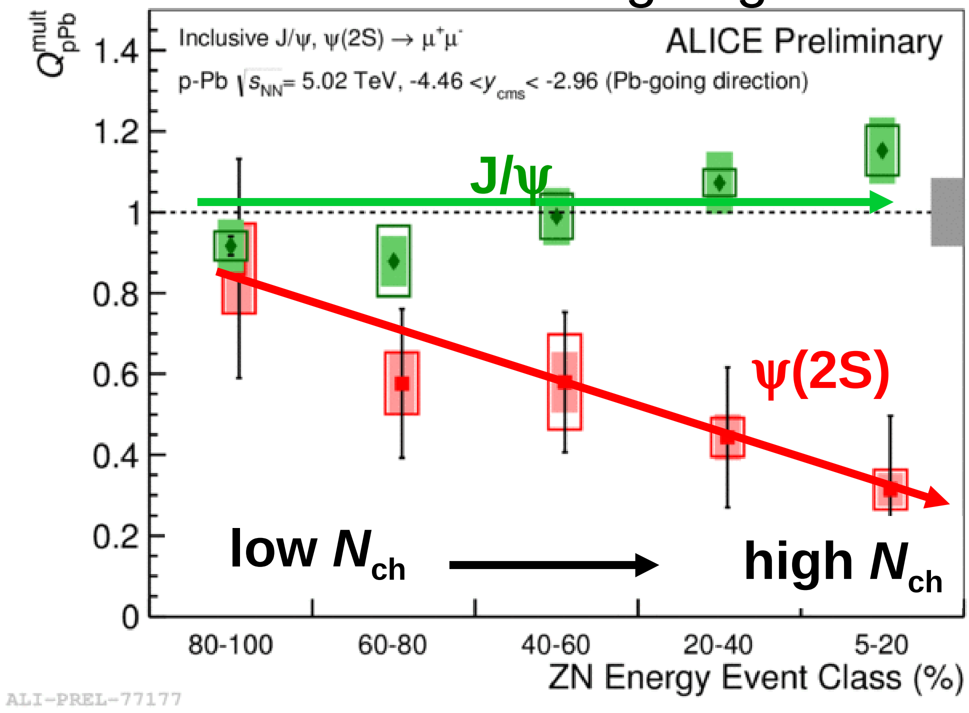
J/Ψ and Ψ(2S) suppression

ALICE, JHEP 06 (2016) 50

Forward going

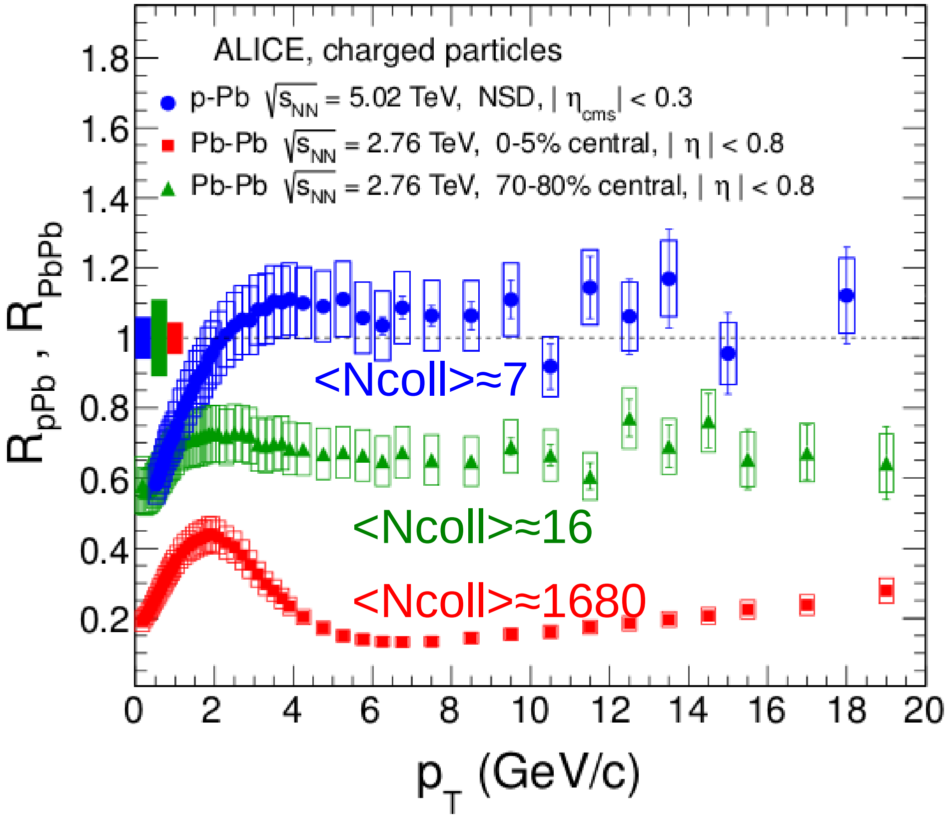


Backward going

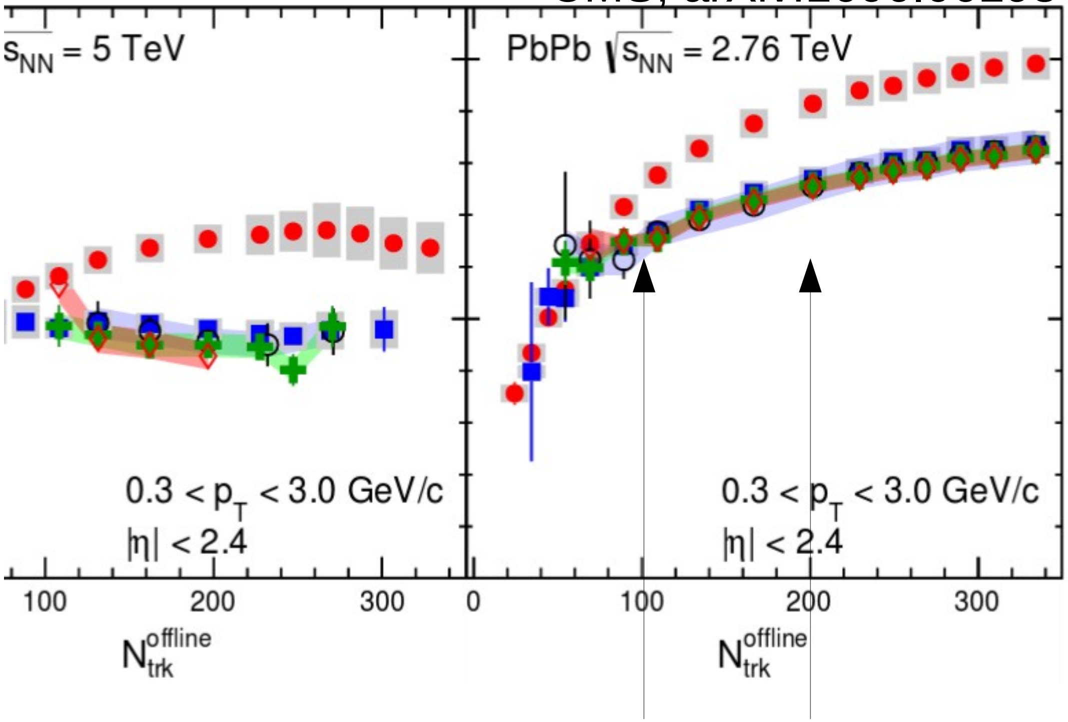


- J/ψ → μμ: Multiplicity dependent suppression in p-going direction, and no suppression in Pb-going direction
  - Consistent with shadowing
- ψ(2S) → μμ: Multiplicity dependent suppression in both directions
  - Needs additional effect (Final state?)
    (see yesterday's discussion in the talk by Elena)

Light flavor: Puzzle for sQGP interpretation



CMS, arXiv:1606.06198

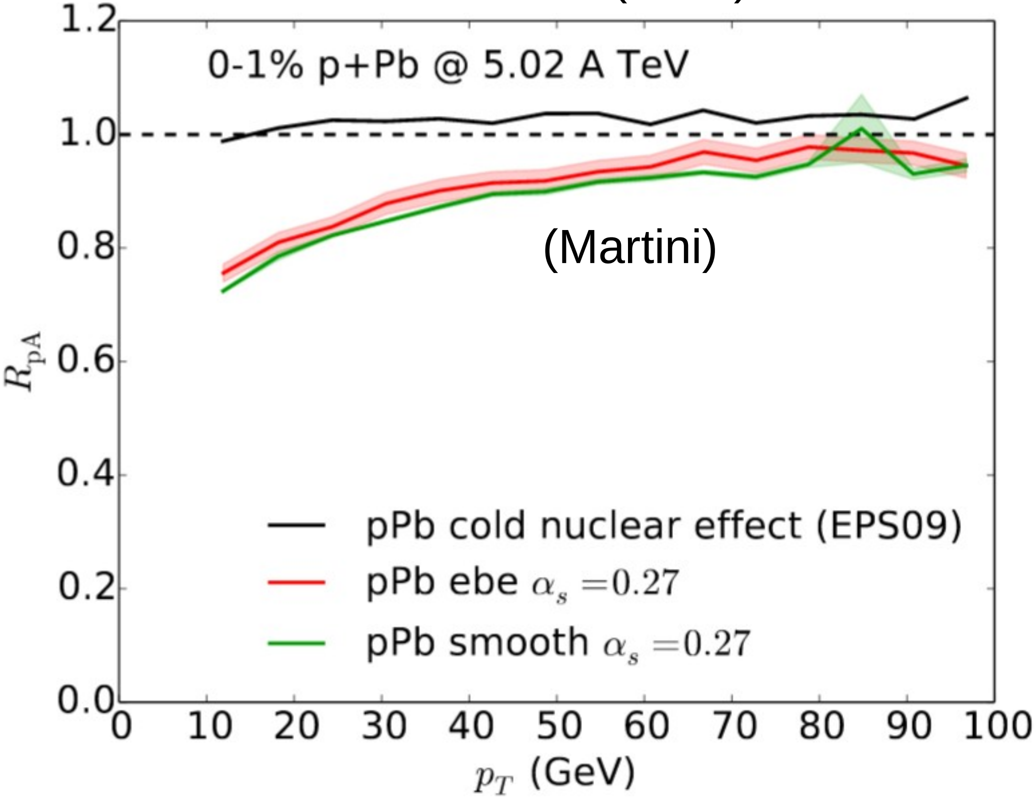


70% 60% centrality

- Large azimuthal anisotropy measured in all systems
- Sizable suppression charged particle spectra in peripheral AA
- Interpretation in AA: “Hydrodynamics and parton energy loss”
  - Naively would expect also parton energy loss in pA!

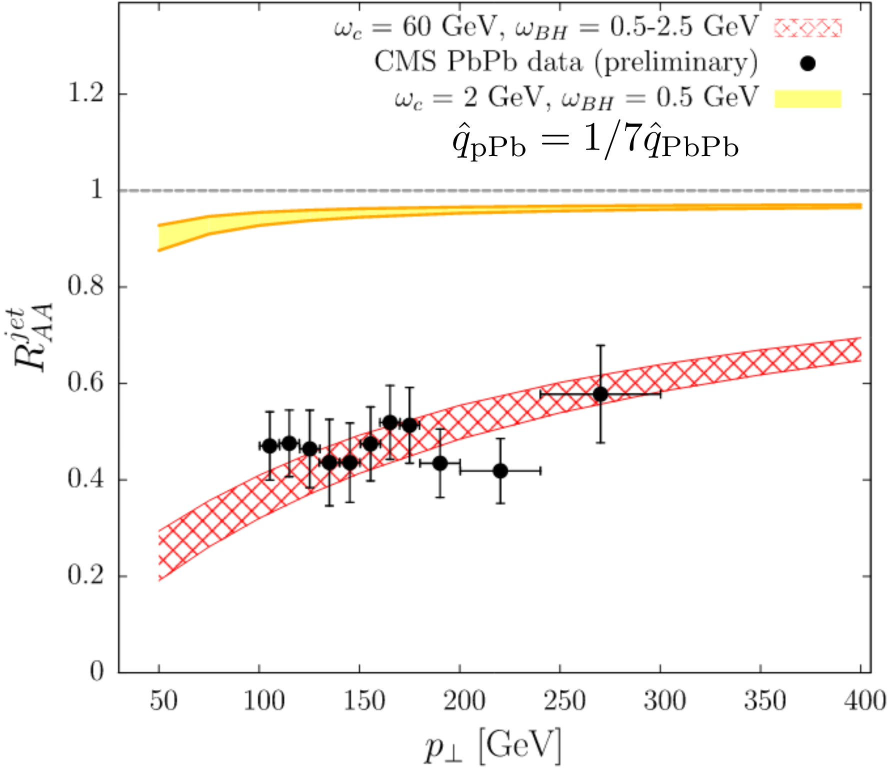
Predictions from models

C.Shen et al., NPA956 (2016) 741

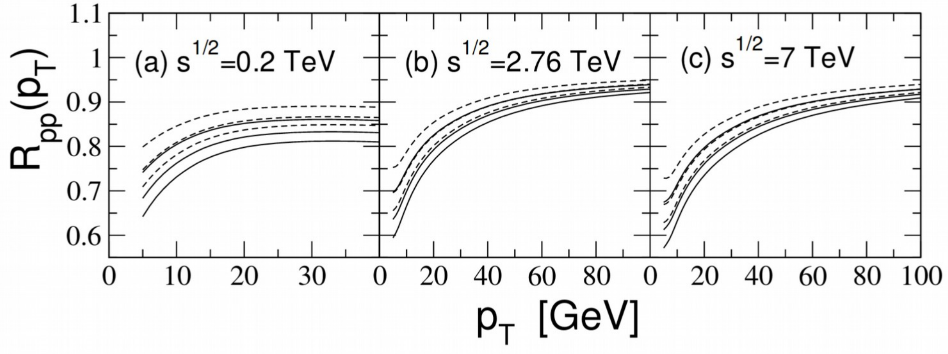


(Martini)

K. Tywoniuk, NPA 926 (2014) 85



B.Zakharov, JPG41 (2014) 075008



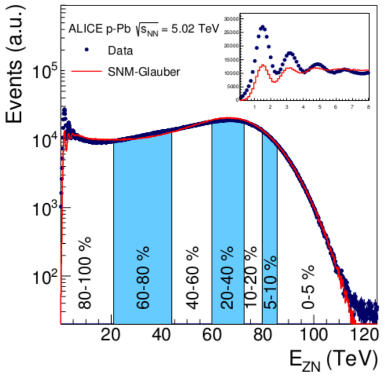
Calculations expect sizable (10-20%) suppression for “central” pPb and pp

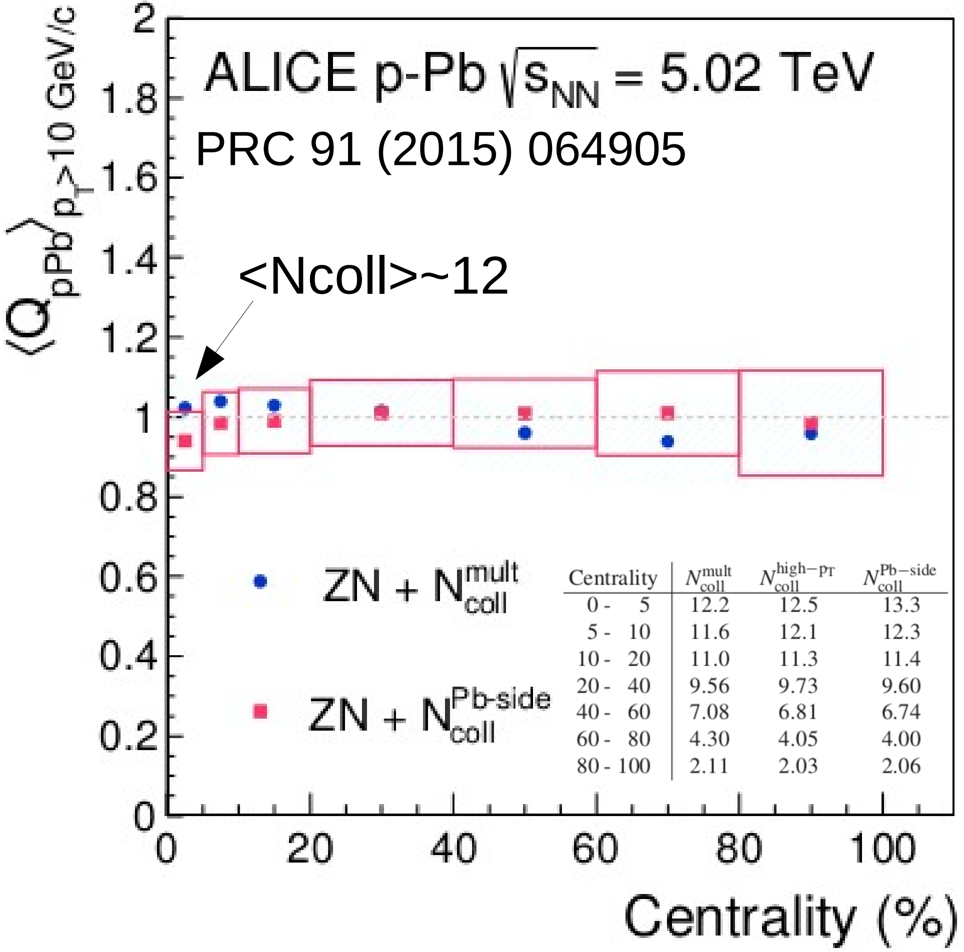
No modification (at low p_T, ie. $x<0.1$)

$$Q_{\mathrm{pPb}}^{ZN} = \frac{1}{N_{\mathrm{coll}}} \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}}$$

(with selection on neutron ZDC on the Pb-side and Ncoll from multiplicity assuming the wounded nucleon model
Ncoll = <Ncoll> * Mult / <Mult>)

ZN on Pb-side

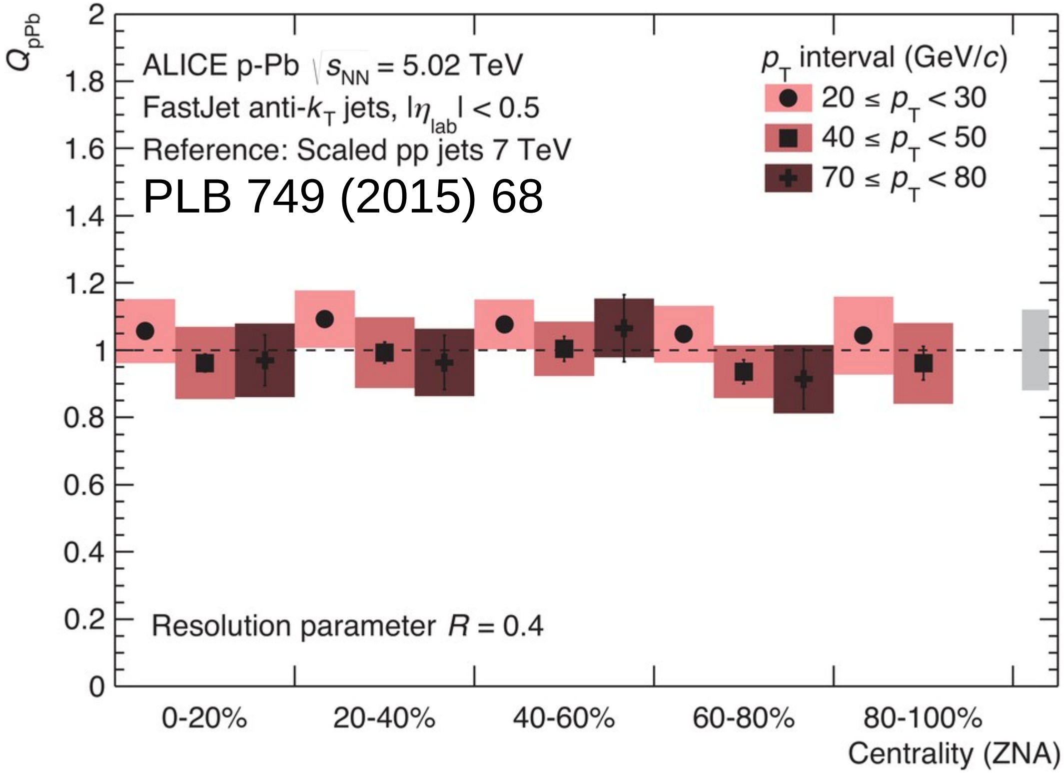




PRC 91 (2015) 064905

<Ncoll>~12

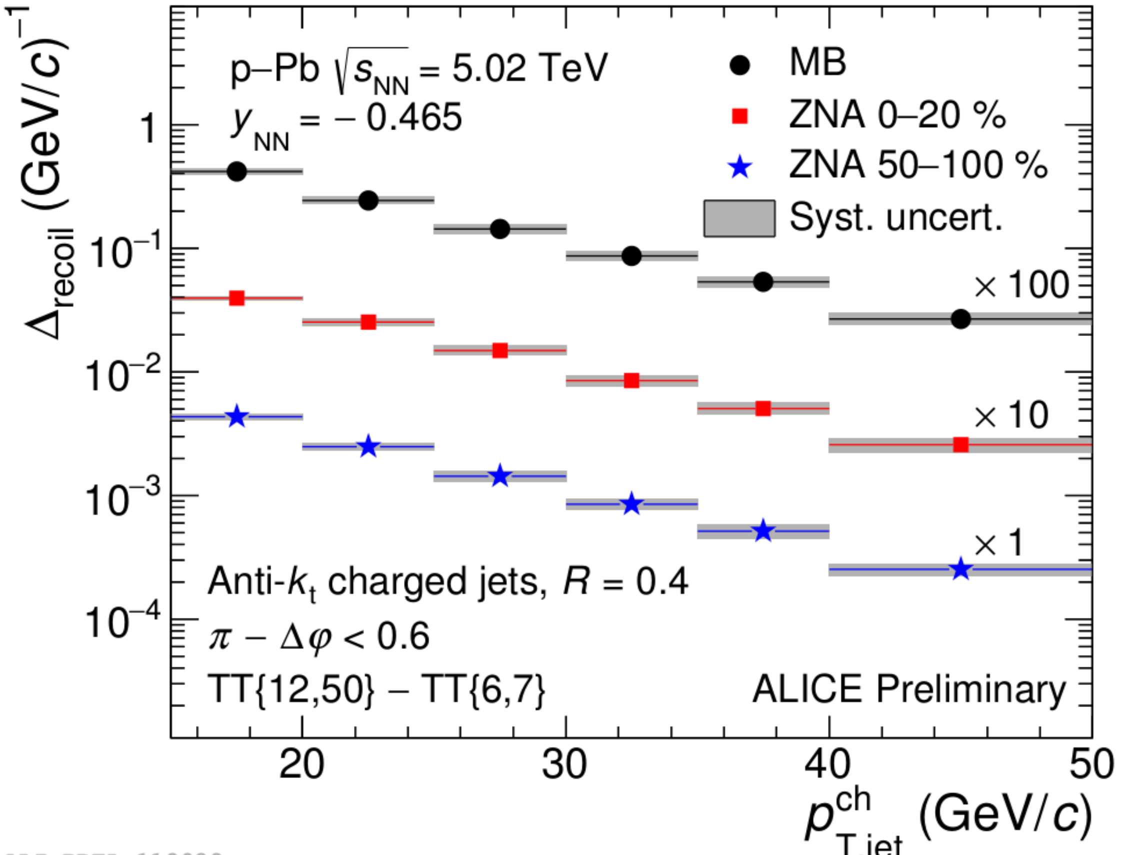
Centrality	$N_{\mathrm{coll}}^{\mathrm{mult}}$	$N_{\mathrm{coll}}^{\mathrm{high-}p_{\mathrm{T}}}$	$N_{\mathrm{coll}}^{\mathrm{Pb-side}}$
0 - 5	12.2	12.5	13.3
5 - 10	11.6	12.1	12.3
10 - 20	11.0	11.3	11.4
20 - 40	9.56	9.73	9.60
40 - 60	7.08	6.81	6.74
60 - 80	4.30	4.05	4.00
80 - 100	2.11	2.03	2.06



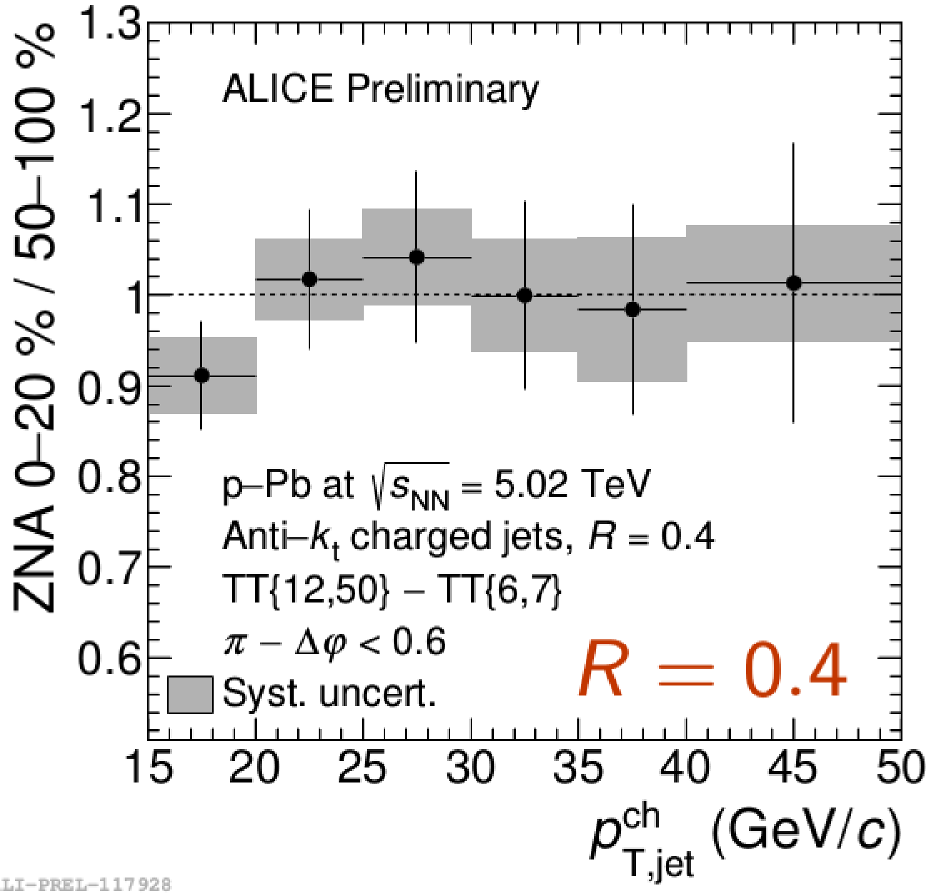
PLB 749 (2015) 68

No suppression observed

Hadron-jet coincidence measurement



ALI-PREL-118028



ALI-PREL-117928

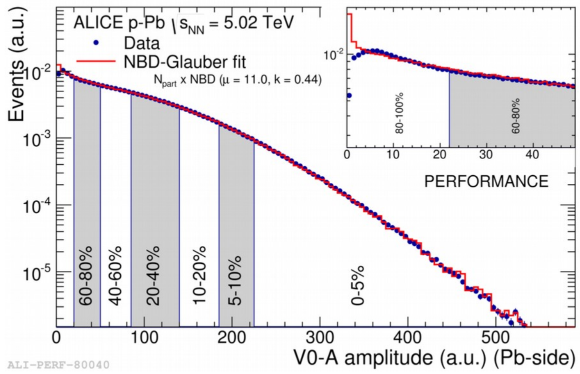
$$\Delta_{\mathrm{recoil}} = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\,\mathrm{d}\eta}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}\{12,50\}} - c_{\mathrm{Ref}} \cdot \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\,\mathrm{d}\eta}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}\{6,7\}}$$

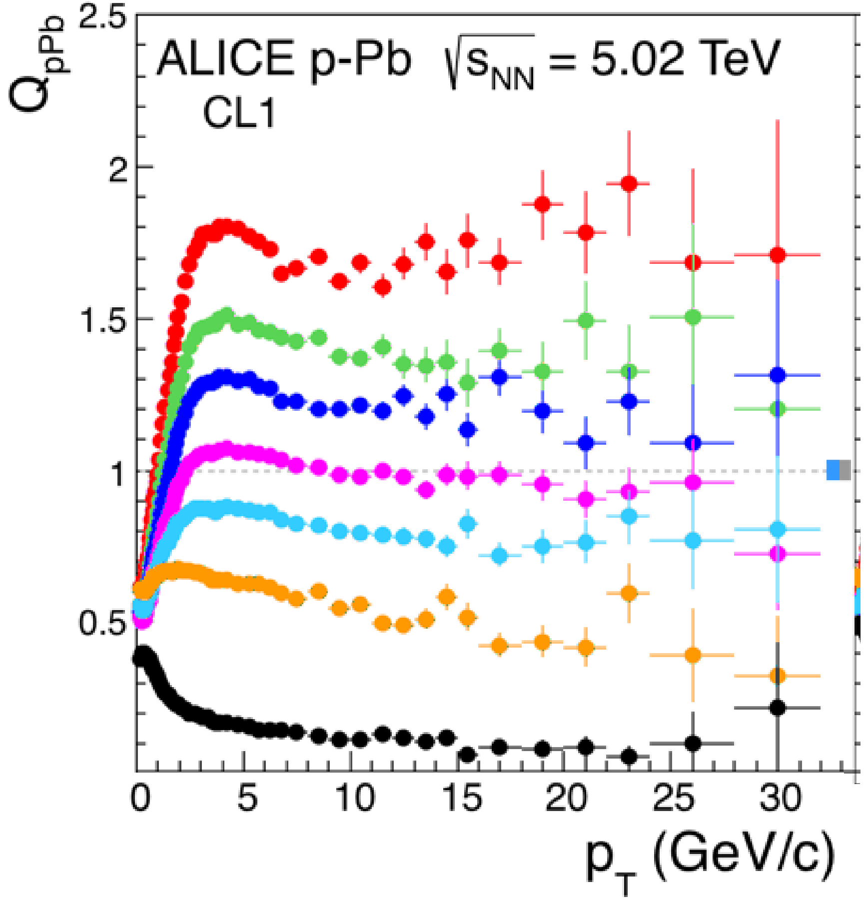
No suppression (precision will improve with large 2015 pPb data!)

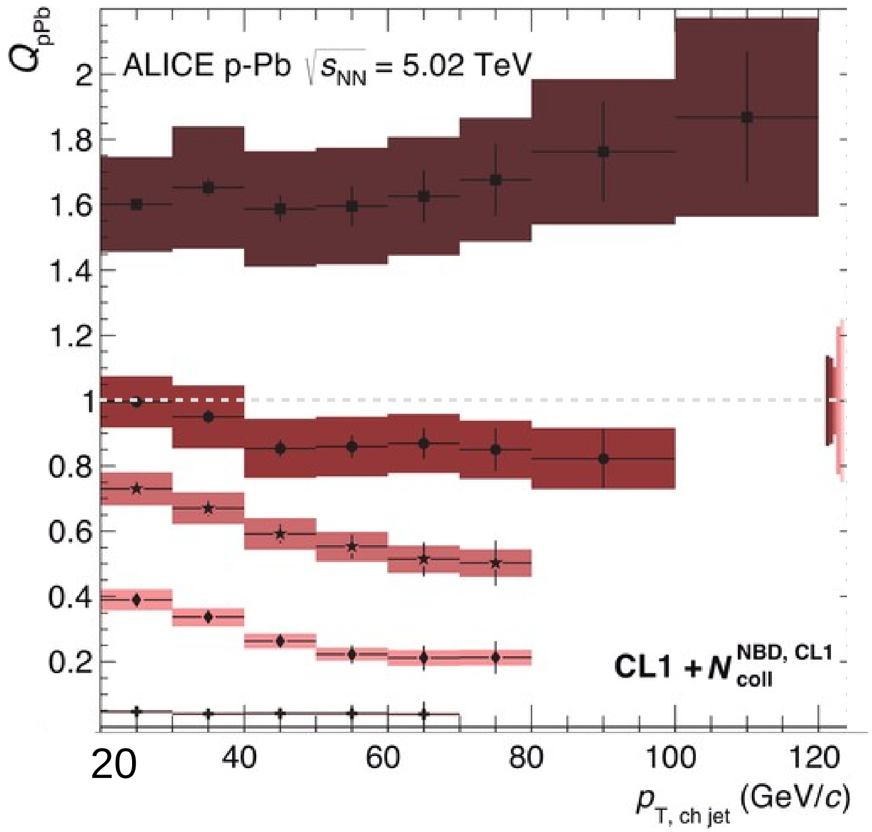
Multiplicity based selection

$$Q_{\mathrm{pPb}} = \frac{1}{N_{\mathrm{coll}}^{\mathrm{fit}}} \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N/\mathrm{d}p_{\mathrm{T}}}$$

(with selection on multiplicity and Ncoll from Glauber fit)







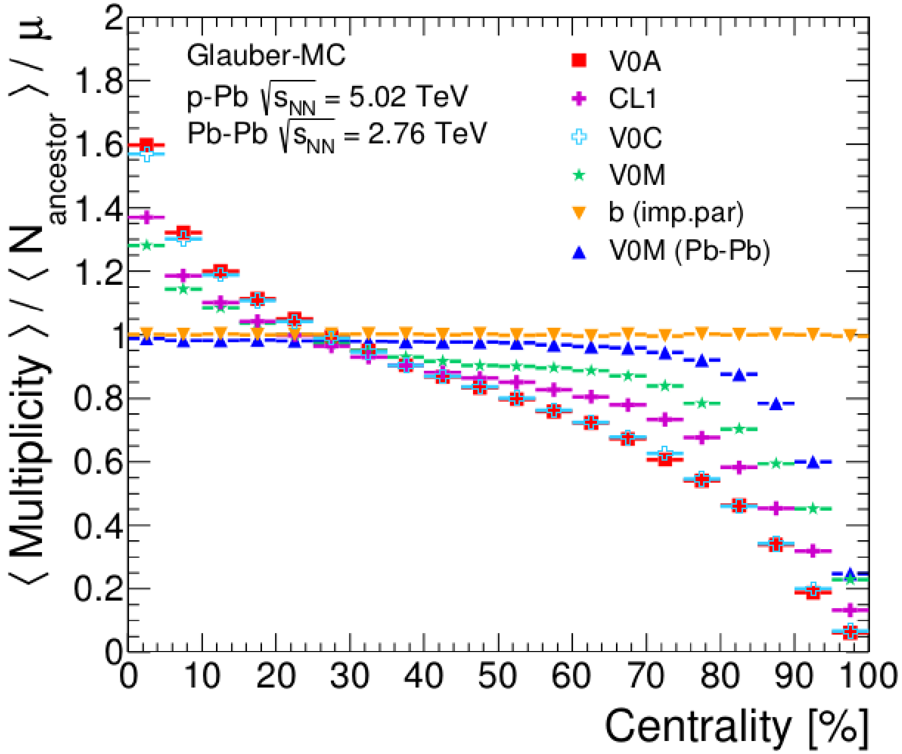
Huge effect

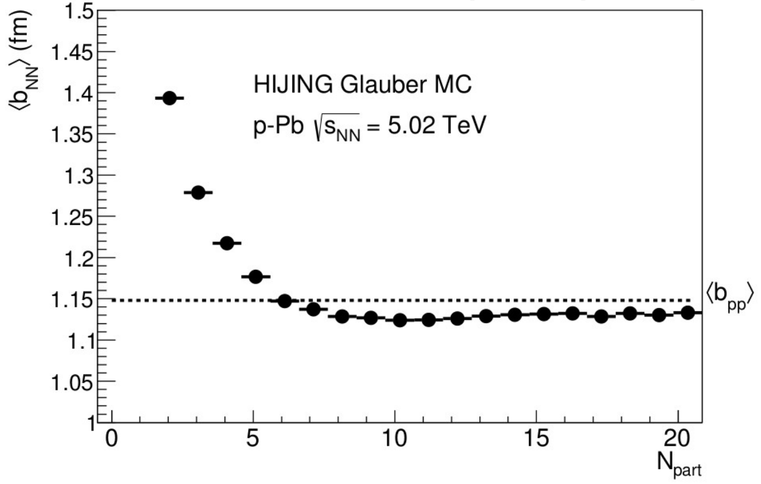
(but QpPb not necessarily one in absence of nuclear modification!)

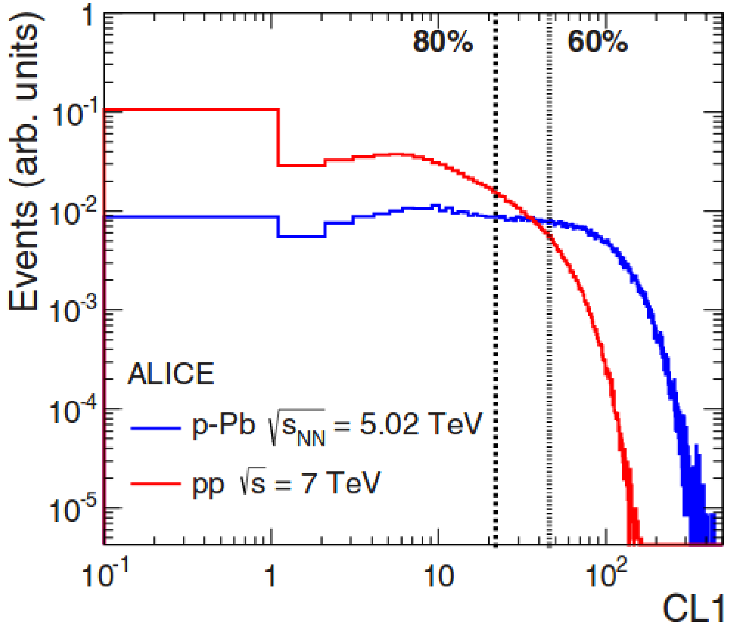
Multiplicity based selection (2)

PRC 91 (2015) 064905

- Several biases are relevant
  - Multiplicity bias
    - Bias on the sources contributing to particle production
  - Jet veto bias
    - Auto-correlation between high p_T particle and soft multiplicity
  - Geometrical bias
    - Average NN impact parameter increases for peripheral collisions (explicitly discussed in J.Jia, PLB 681 (2009) 320)







Multiple parton interactions (MPI)

- Naive factorization

$$\langle n_{2\to2}\rangle = \frac{\sigma_{2\to2}}{\sigma_{\mathrm{tot}}}$$

>1 at pert. scale

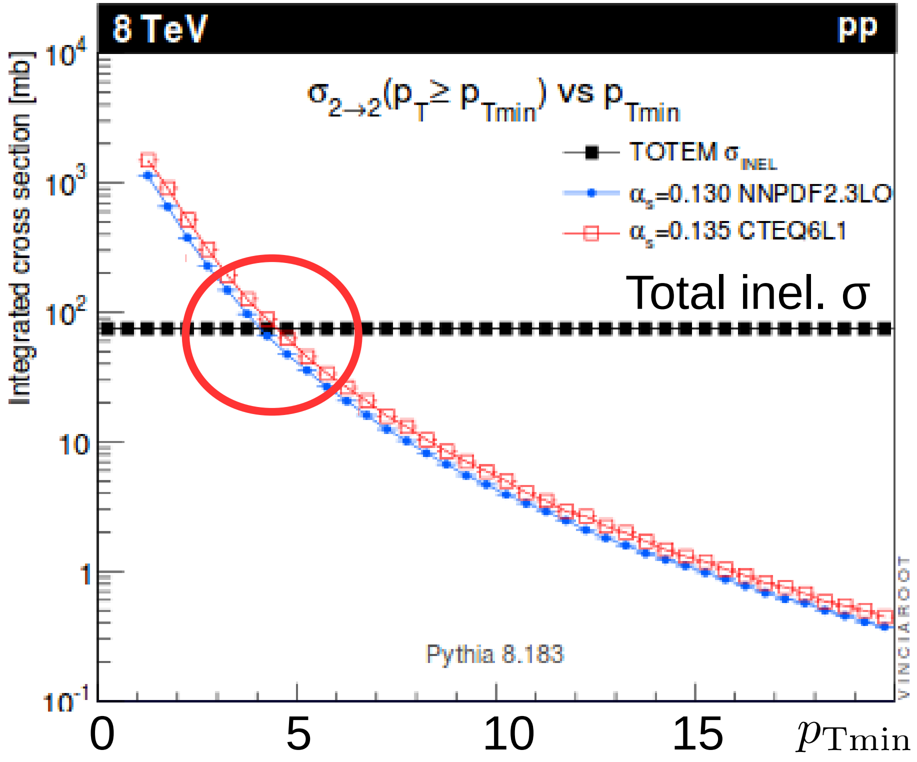
$$P_n = \frac{\langle n_{2\to2}\rangle^n}{n!}\, exp\left(-\langle n_{2\to2}\rangle\right)$$

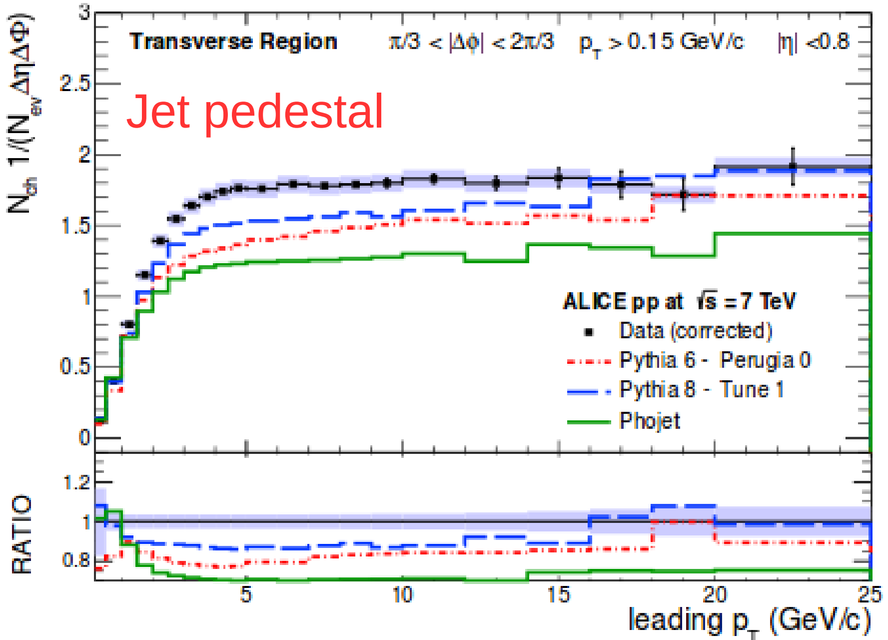
- Realistic models (eg. PYTHIA)
  - Color screening to regularize hard cross section at low p_T
  - Cut-off at high n because of energy conservation
  - Coherence between scatters
  - Impact parameter dependence

$$n_{\mathrm{hard}}(b) = \sigma_{\mathrm{hard}} T_{\mathrm{p}}(b)$$

    - Leads to a correlation between hard and soft particles as in AA

Skands, arXiv:1207.2389





MPI model in HIJING

PRD44 (1991) 3501

Inelasticic NN collision at b_{NN} given as

$$\sigma_{\mathrm{inel}} \propto 1 - e^{(\sigma_{\mathrm{soft}}+\sigma_{\mathrm{hard}})T_{\mathrm{N}}(b_{\mathrm{NN}})}$$

with nuclear overlap (Eikonal function)

$$T_{\mathrm{N}} \propto (\xi\mu)^3 K_3(\xi\mu) \;\; \text{with } \xi = b_{\mathrm{NN}}/b_0$$

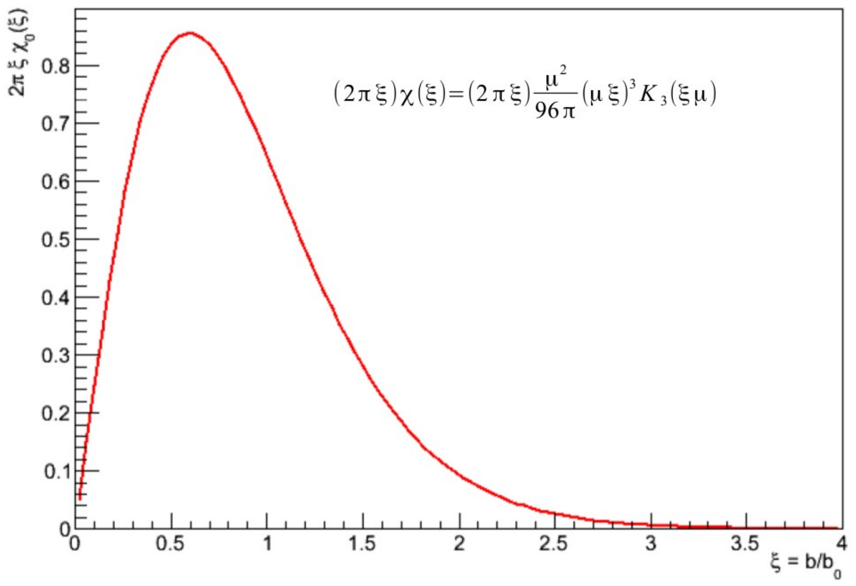
Number of hard (mpi) collisions given by

$$P(n_{\mathrm{hard}}) = \frac{\langle n_{\mathrm{hard}}\rangle^{n_{\mathrm{hard}}}}{n_{\mathrm{hard}}!} e^{-\langle n_{\mathrm{hard}}\rangle}$$

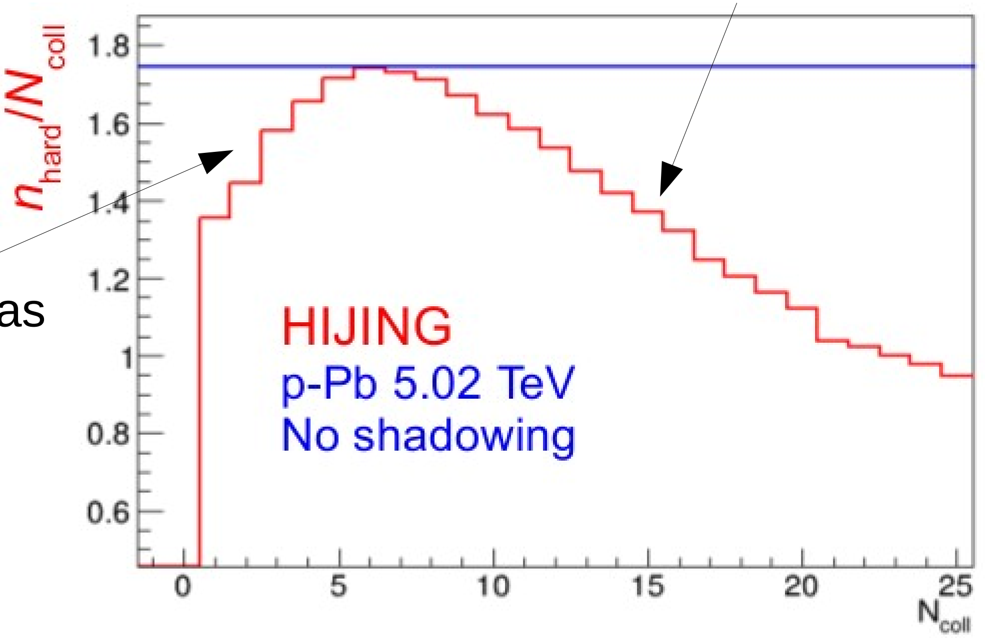
with

$$\langle n_{\mathrm{hard}}\rangle = \sigma_{\mathrm{hard}} T_{\mathrm{N}}$$

Eikonal function

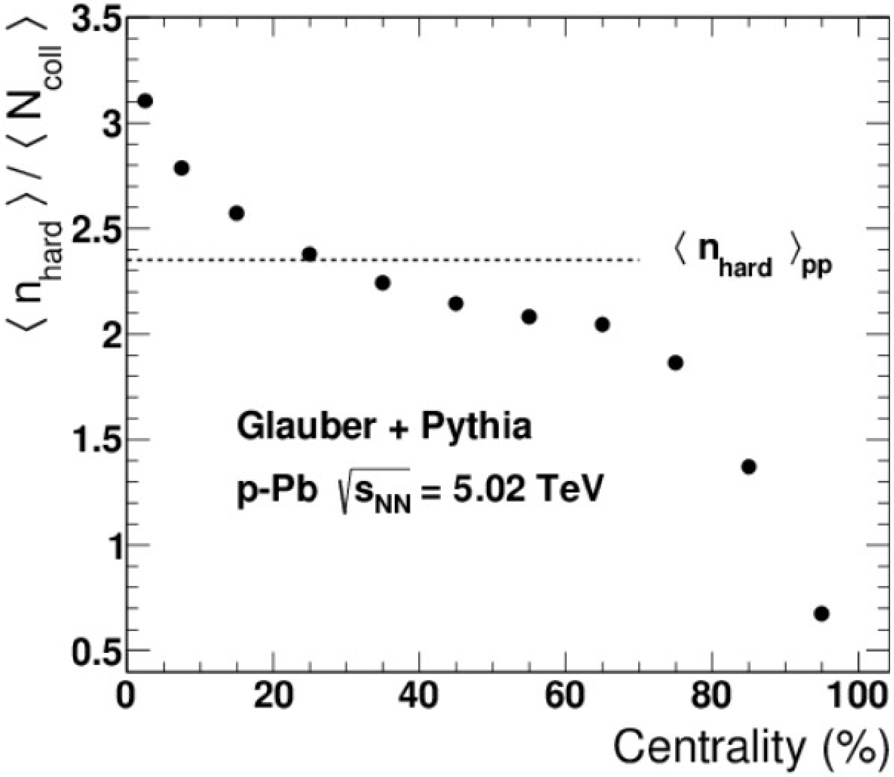


Energy-momentum conservation

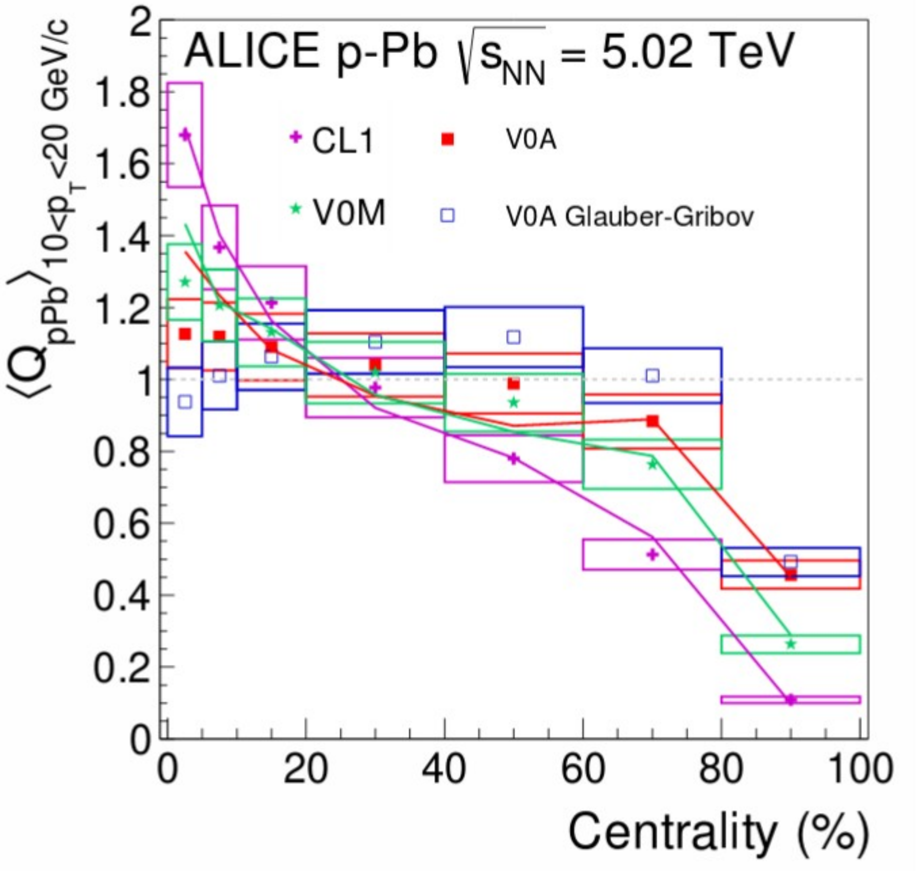


Geometry bias

Demonstration using Glauber+Pythia



ALICE, PRC 91 (2015) 064905



G-PYTHIA:

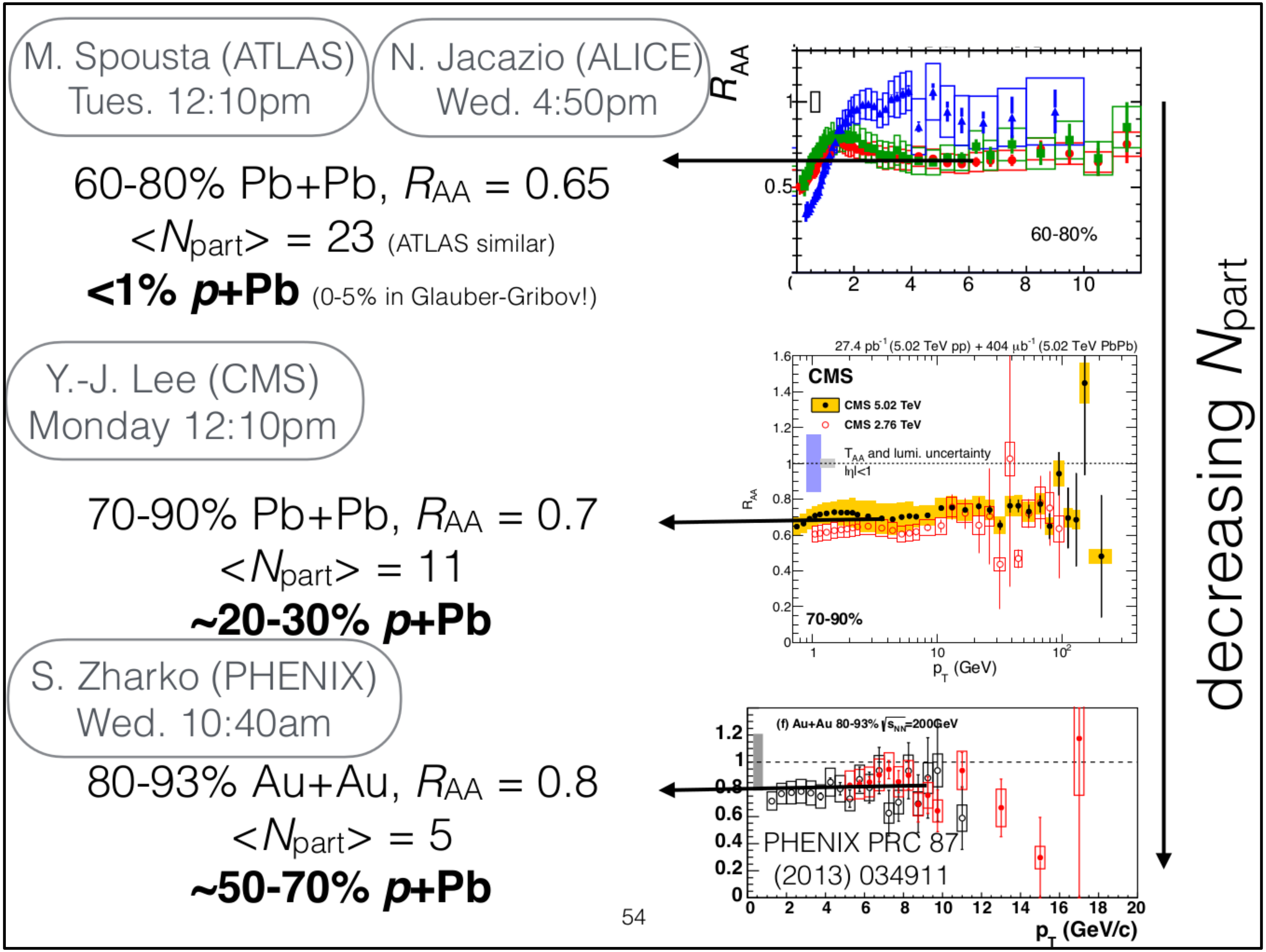
1. For a given Glauber event, simulate Ncoll many PYTHIA pp events
2. Order events according to resulting total multiplicity (in given phase space)

Suggests, at high p_T

$$\langle Q_{\mathrm{pPb}}\rangle \propto \frac{N_{\mathrm{hard}}}{\mathrm{N}_{\mathrm{coll}}\,\langle \mathrm{N}^{\mathrm{pp}}_{\mathrm{hard}}\rangle}$$

What about (peripheral) AA?

Dennis Perepelitsa (QM 2017)



M. Spousta (ATLAS)
Tues. 12:10pm

N. Jacazio (ALICE)
Wed. 4:50pm

60-80% Pb+Pb, $R_{AA} = 0.65$

$\langle N_{part} \rangle = 23$ (ATLAS similar)

<1% *p*+Pb (0-5% in Glauber-Gribov!)

Y.-J. Lee (CMS)
Monday 12:10pm

70-90% Pb+Pb, $R_{AA} = 0.7$

$\langle N_{part} \rangle = 11$

~20-30% *p*+Pb

S. Zharko (PHENIX)
Wed. 10:40am

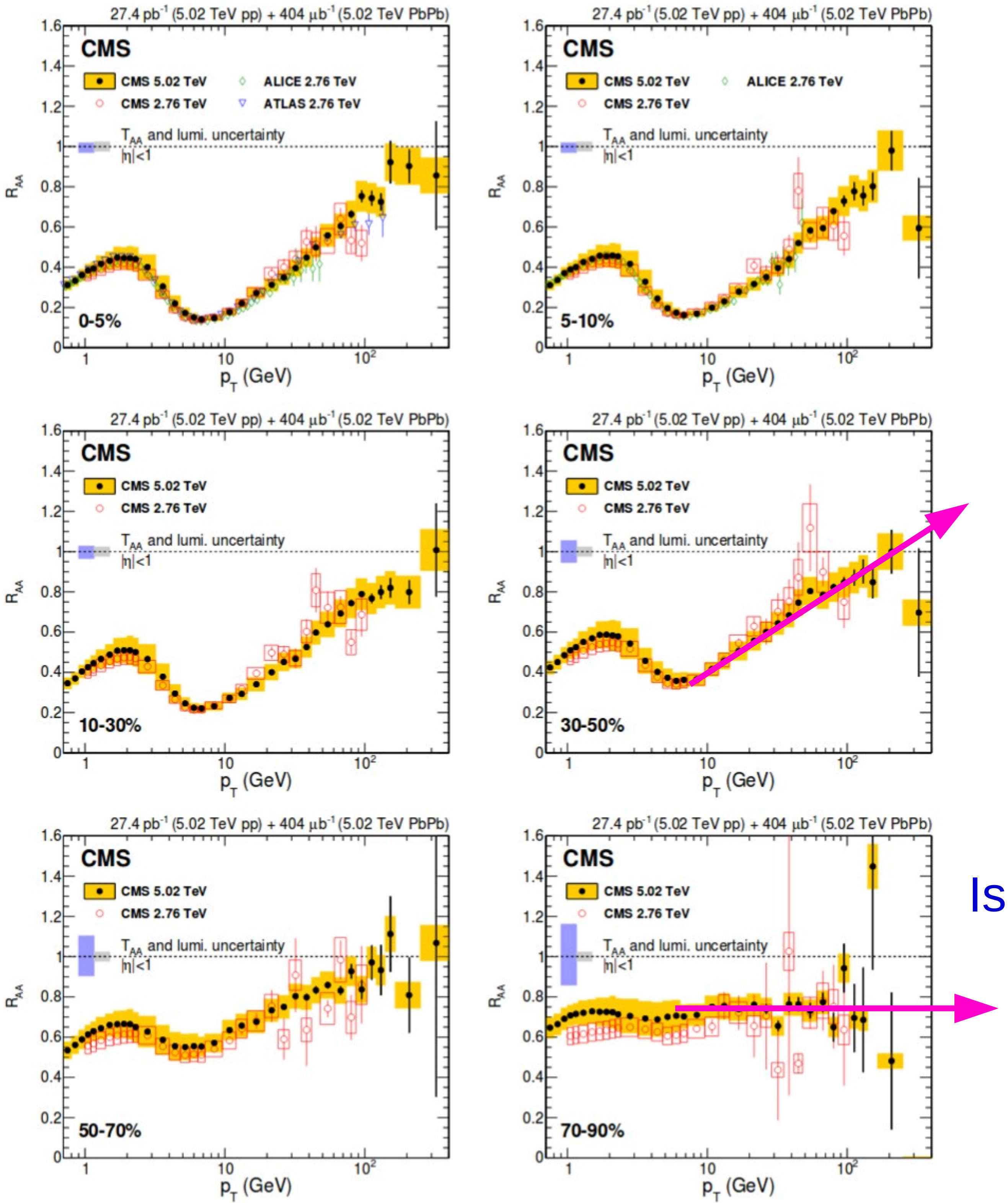
80-93% Au+Au, $R_{AA} = 0.8$

$\langle N_{part} \rangle = 5$

~50-70% *p*+Pb

54

JHEP 04 (2017) 039



Rising and approaching R~1!

Is it a multiplicity bias?

Seemingly constant at around R~0.8

Model comparison

Idea: Use model without quenching but perform event ordering (slicing) for forward multiplicity just as in data

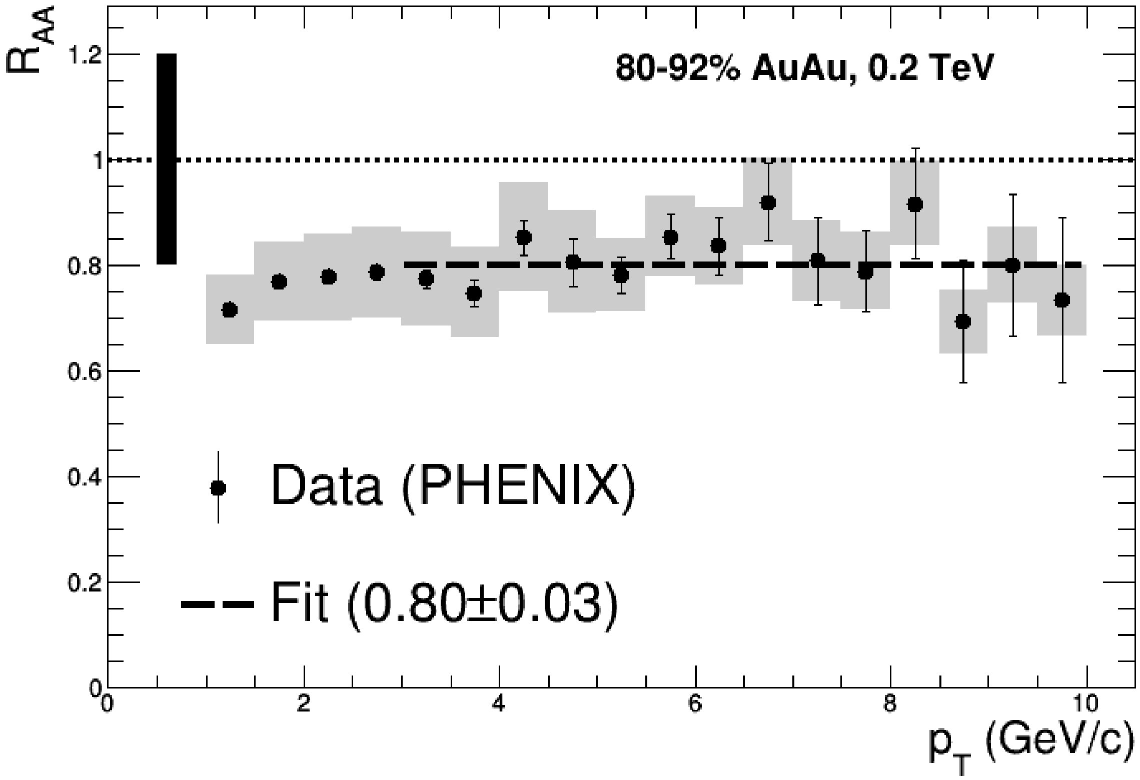
Hijing:

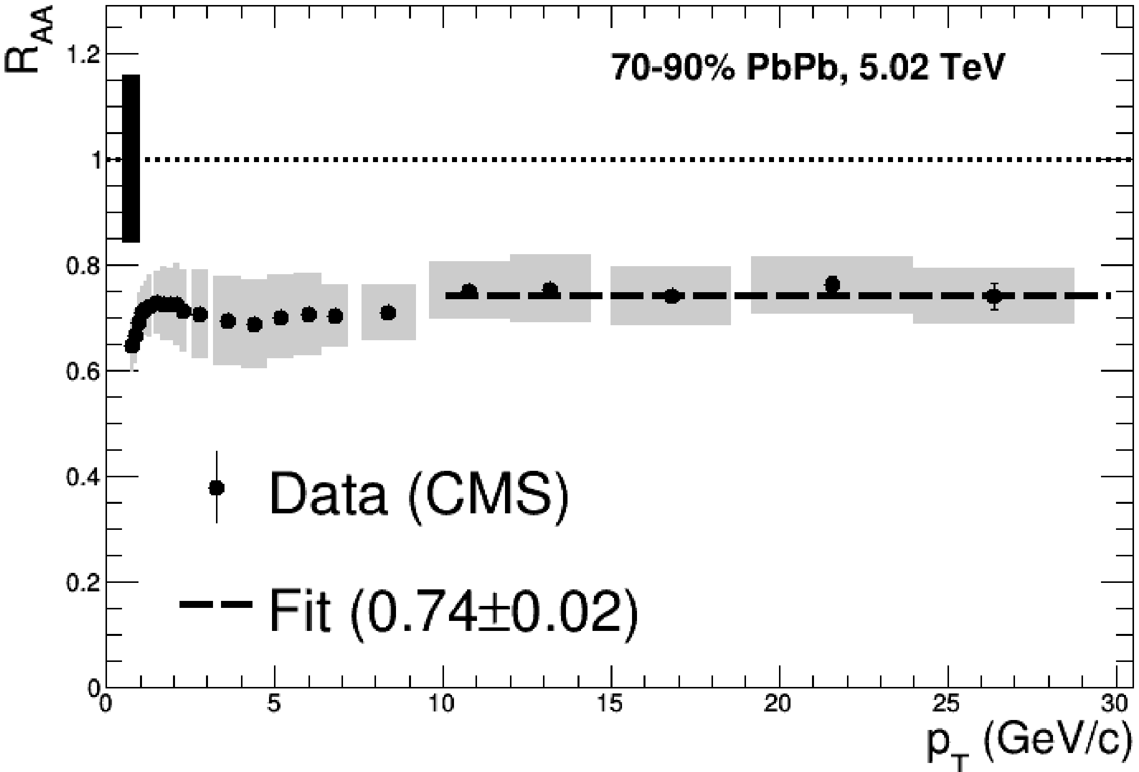
- No quenching, no shadowing, but ad-hoc momentum conservation and multiple scattering
- Does not give $R_{AA} \rightarrow 1$ at high p_T for central collisions

HG-Pythia:

- Use HIJING nhard distribution as input and superimpose correspondingly PYTHIA (Perugia 2011) events
- Does not reproduce multiplicity

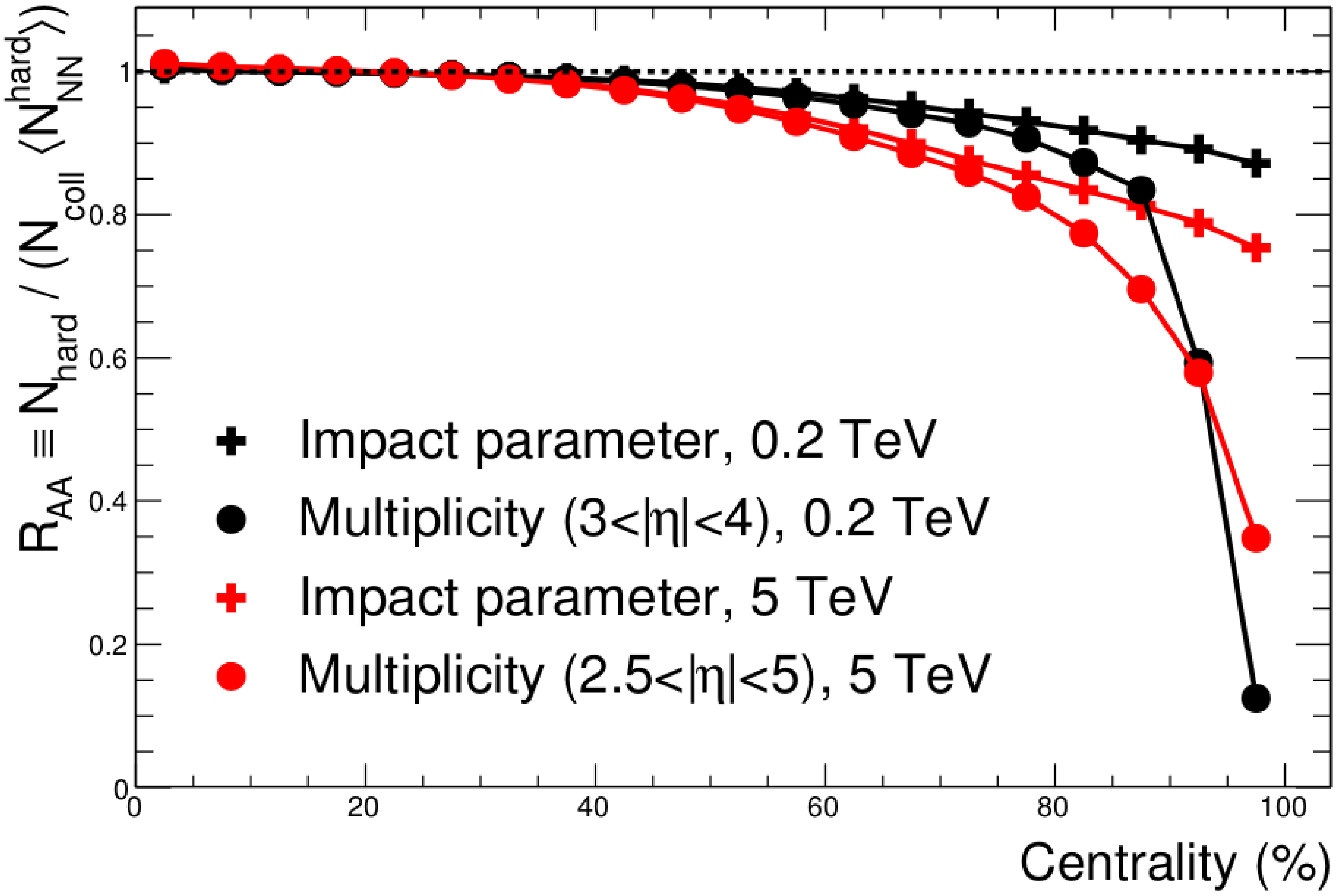
Multiplicity bias can cause the apparent suppression!





Multiplicity and geometry bias effect

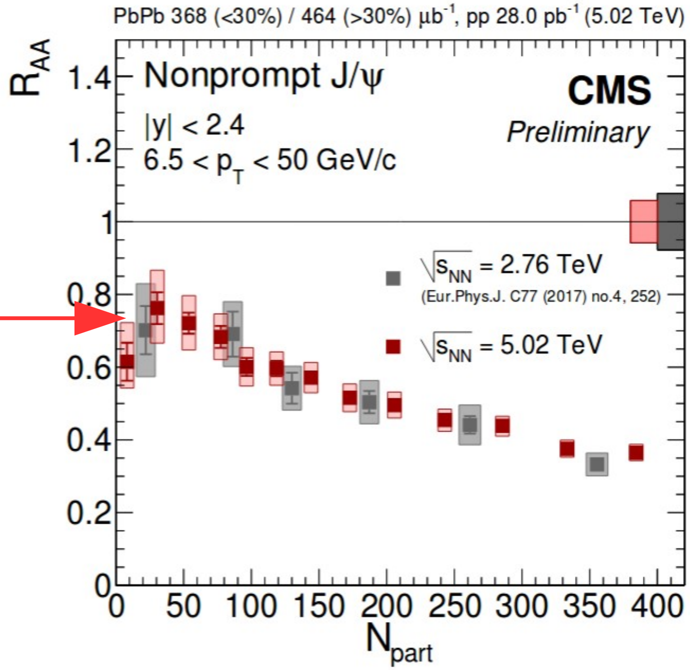
A.Morsch + C.L.,
arXiv:1705.08856



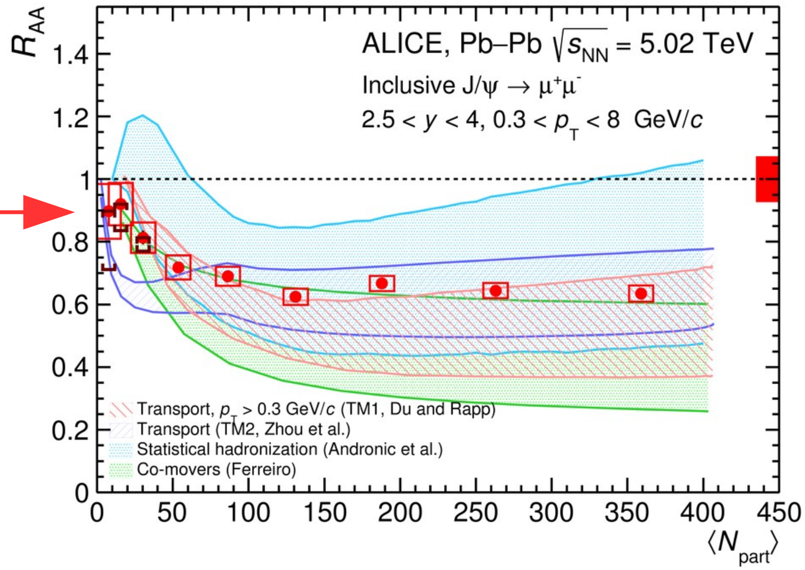
Peripheral collisions strongly affected by multiplicity bias

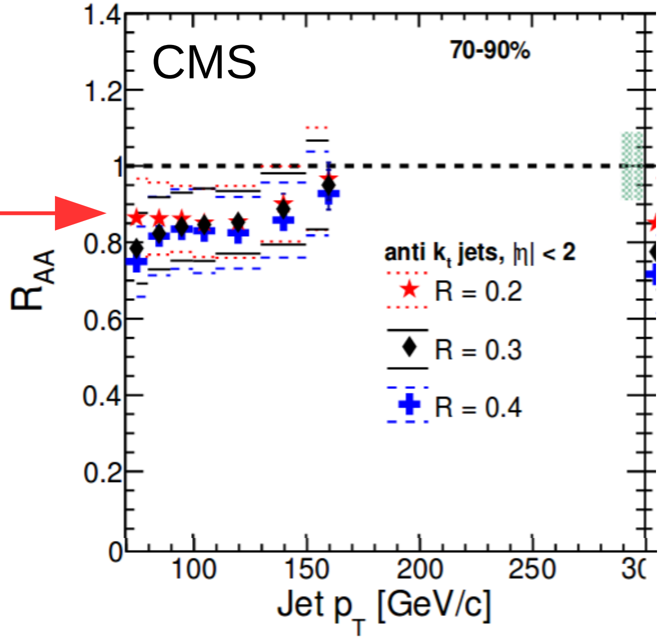
Implications

- Toy model study suggests that apparent suppression in very (80++%) peripheral AA originates from multiplicity/geometry bias
  - Relevant for all hard probes
  - Beware use of R_{CP}
  - At lower energies (BES) be aware of jet veto bias

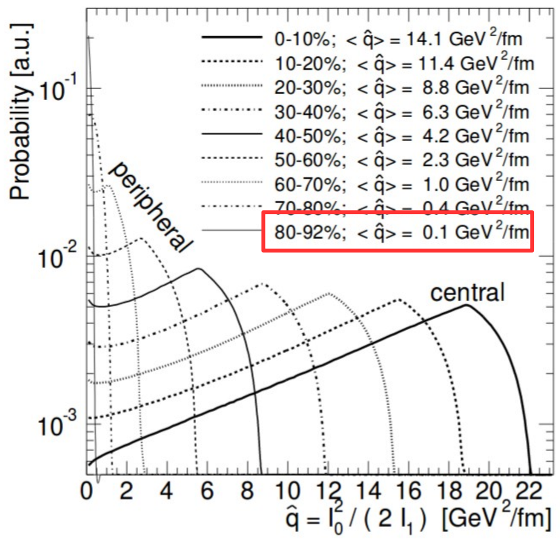


CMS PAS HIN-16-025

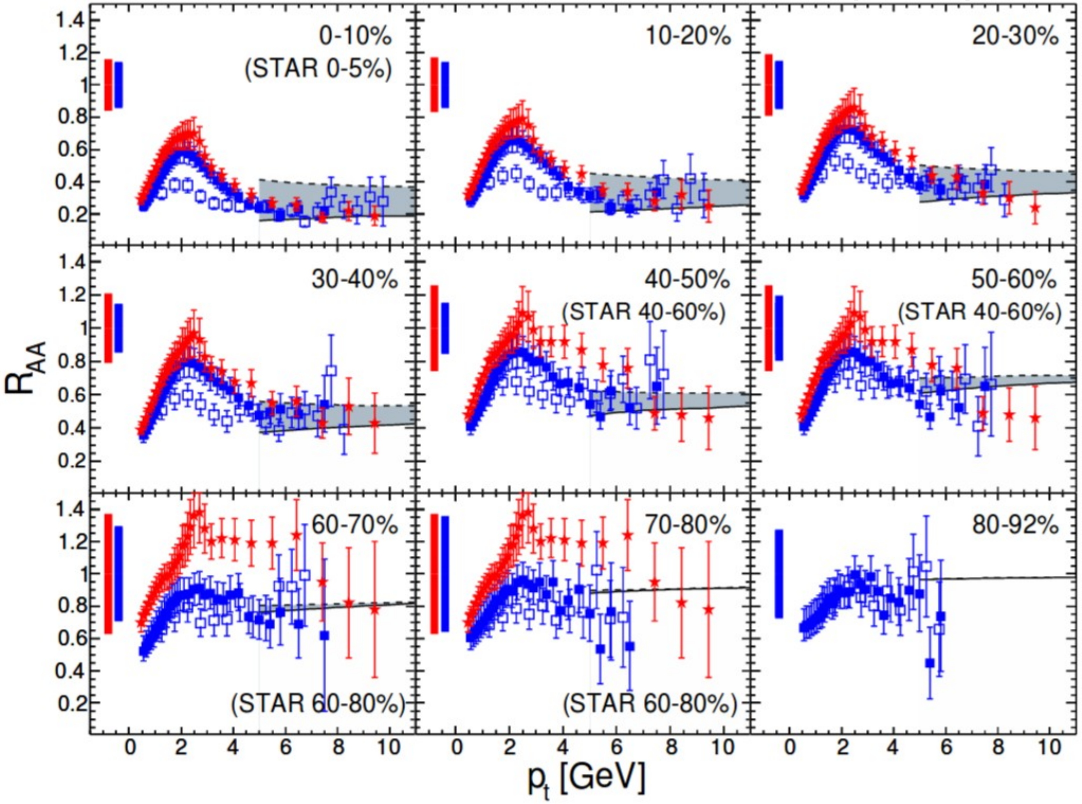


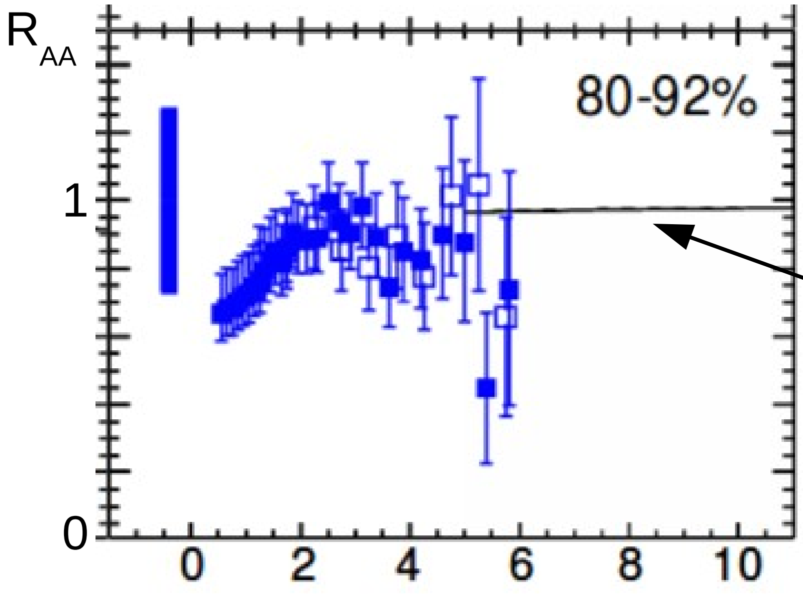


Parton quenching calculation (~2004)



A.Dainese, G.Paic, C.L., EPJC 38 (2005) 461

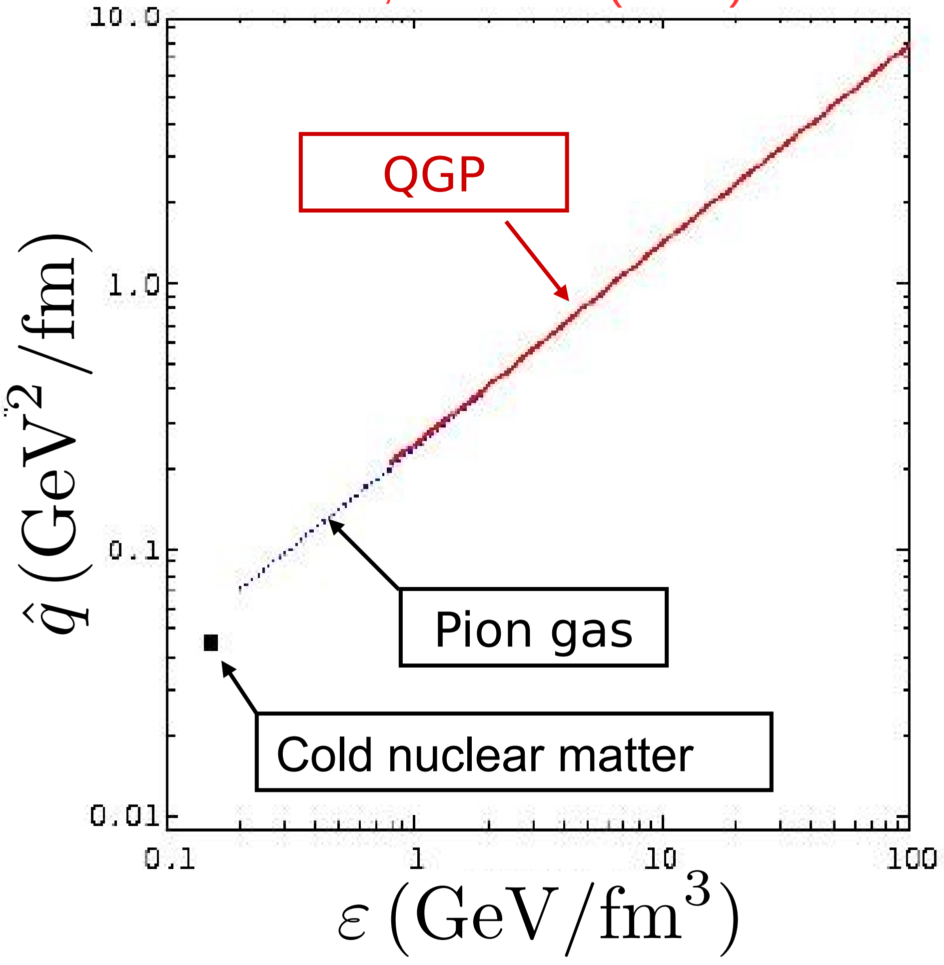




Indeed only very small suppression (3%) from (old) PQM calculation

Implications for “low density systems”

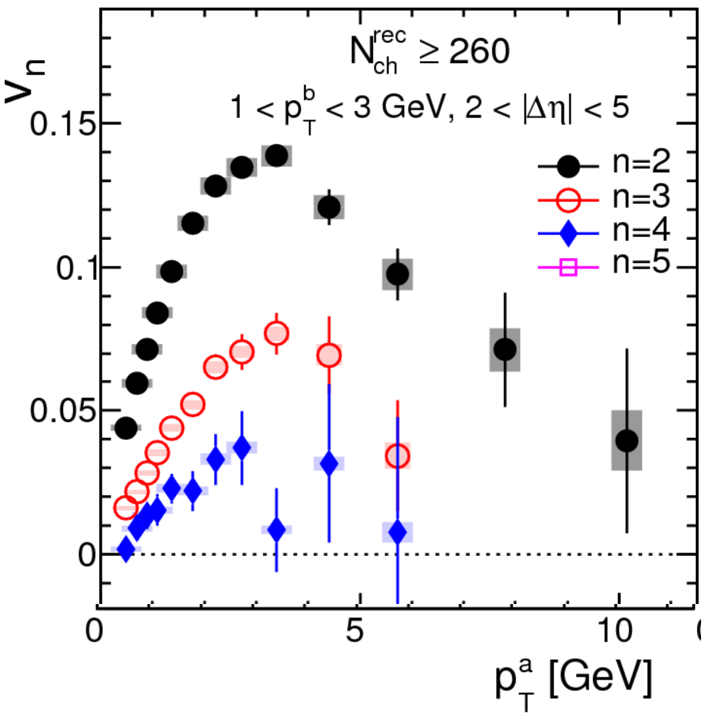
- Expect evolution of “parton energy loss to be continuous”
  - Natural explanation that it turns off both at low mult of very peripheral AA and pPb
    - Could be similar to that of pion gas or even cold nuclear matter
- Observation of “large” v_2 and no “obvious” parton energy loss consistent across
  - all systems
  - all energies (BES)
- However, does not mean the effect is absent in high mult pPb
  - focus on the high mult region (>200 Ntracks)

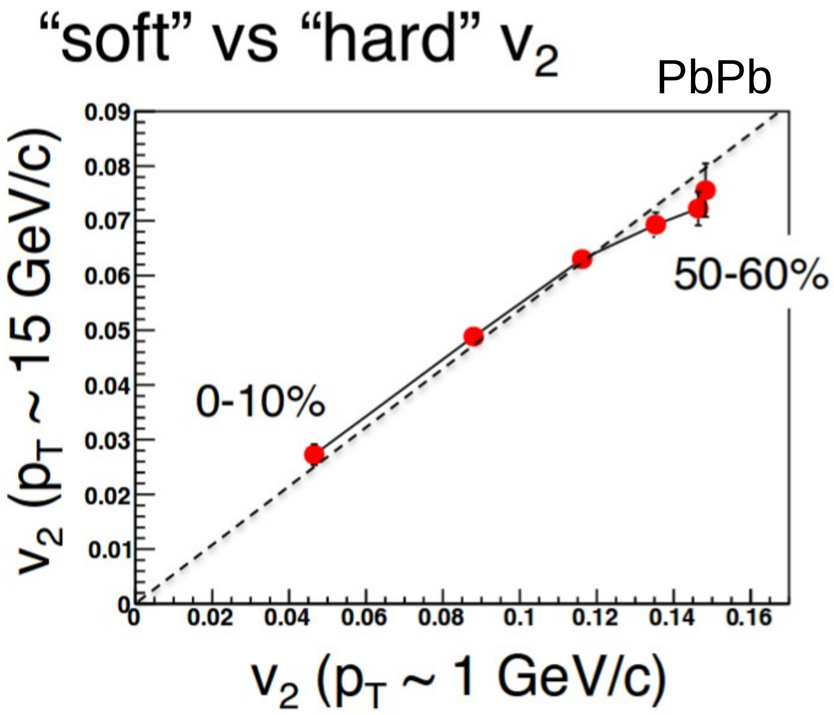


Baier, NPA 715 (2003) 209

What next ...

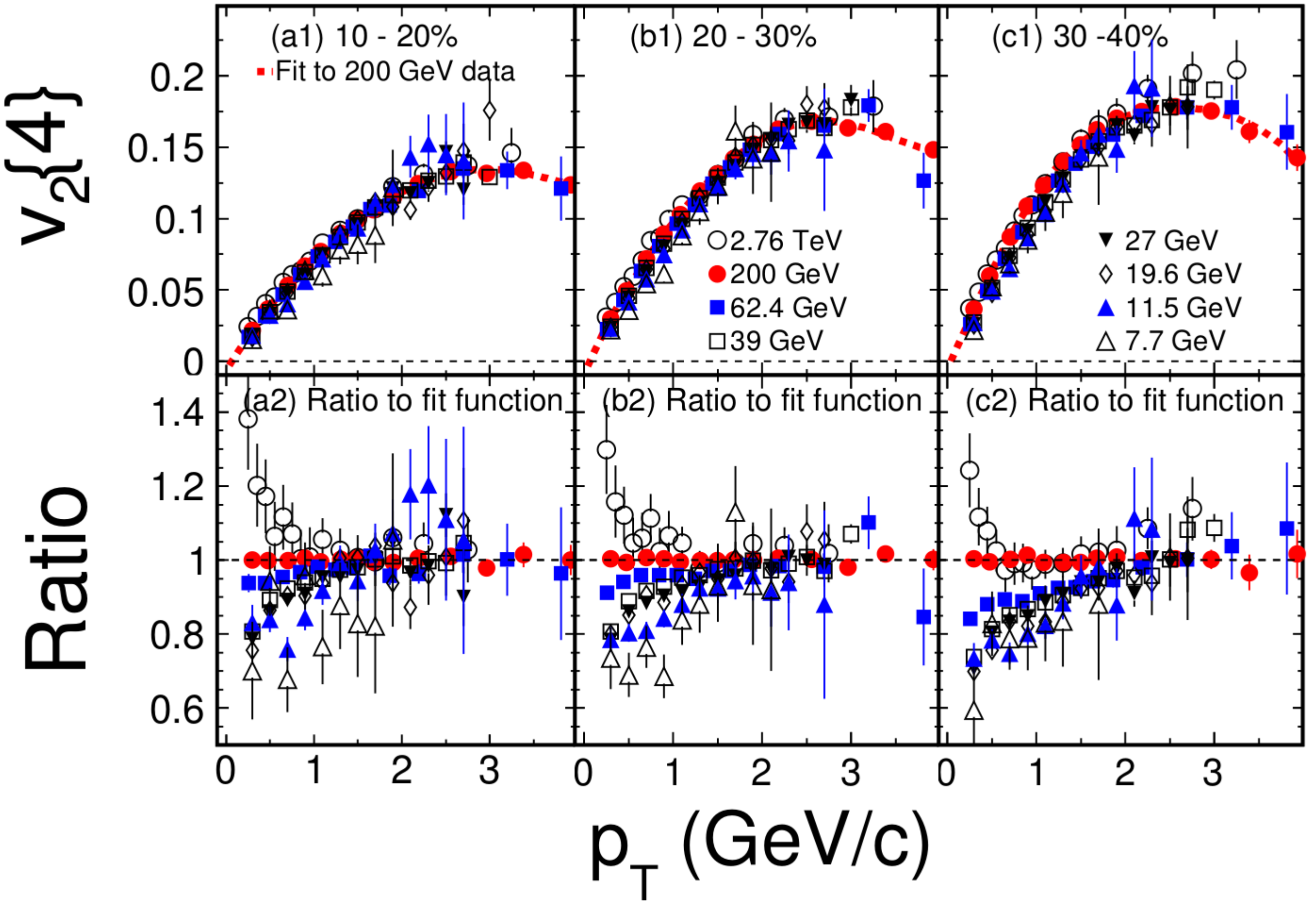
- Measure v_N in pPb (and very peripheral PbPb) to higher p_T
  - Would be good to get predictions at ~10-20 GeV from parton energy loss
- Semi-inclusive measurements
  - T_{AB} cancels
- Study peripheral AA
  - Establish effect in data directly
  - Measure a “candle” cross section
    - Difficult
  - “soft vs hard” v_2 correlation

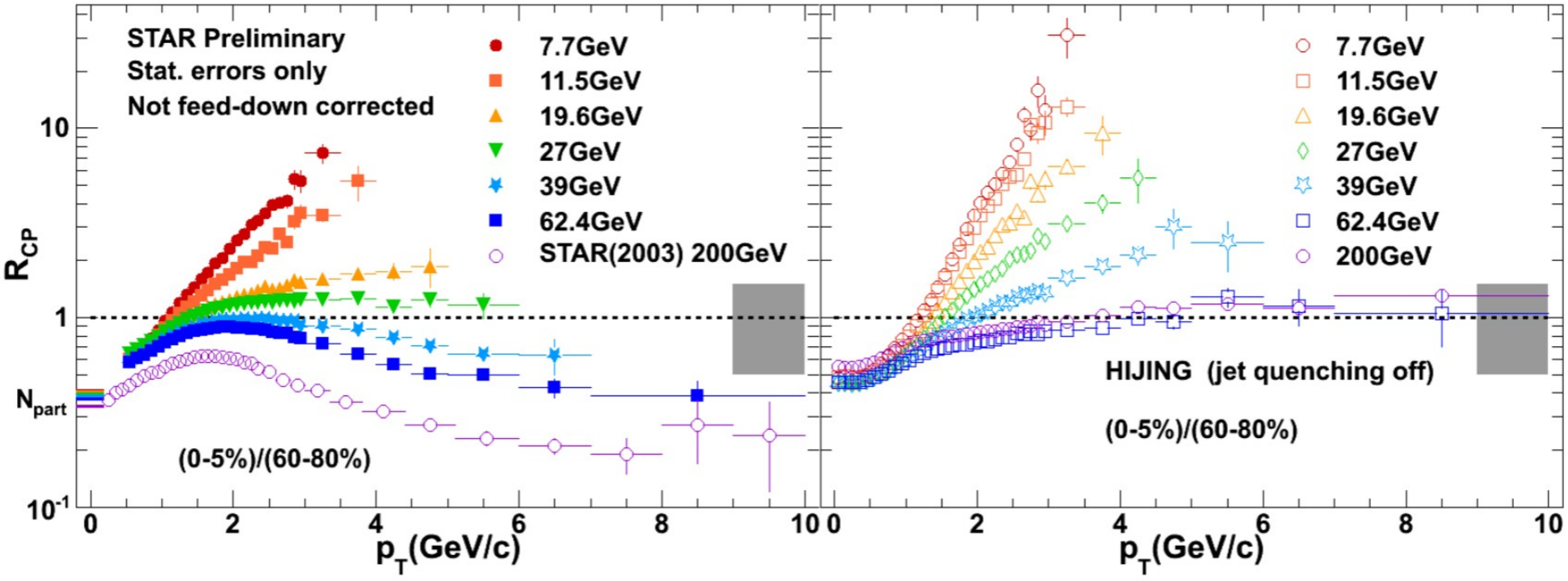




Extra

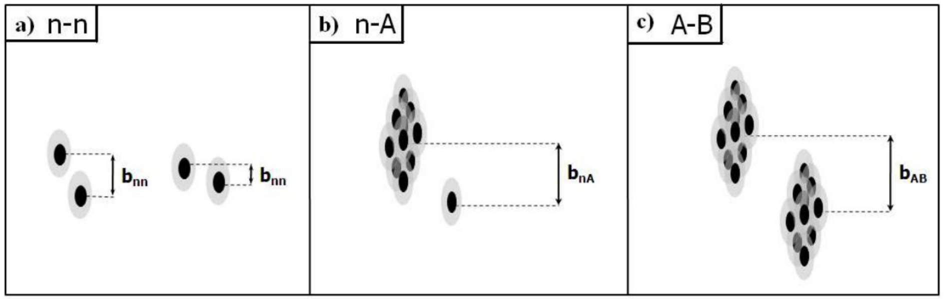
Energy scan


(a1) 10 - 20%
Fit to 200 GeV data
(b1) 20 - 30%
(c1) 30 -40%
v2{4}
0.2
0.15
0.1
0.05
0
2.76 TeV
200 GeV
62.4 GeV
39 GeV
27 GeV
19.6 GeV
11.5 GeV
7.7 GeV
(a2) Ratio to fit function
(b2) Ratio to fit function
(c2) Ratio to fit function
Ratio
1.4
1.2
1
0.8
0.6
0
1
2
3
pT (GeV/c)


STAR Preliminary
Stat. errors only
Not feed-down corrected
7.7GeV
11.5GeV
19.6GeV
27GeV
39GeV
62.4GeV
STAR(2003) 200GeV
RCP
10
1
Npart
10-1
(0-5%)/(60-80%)
0
2
4
6
8
10
pT(GeV/c)
7.7GeV
11.5GeV
19.6GeV
27GeV
39GeV
62.4GeV
200GeV
HIJING (jet quenching off)
(0-5%)/(60-80%)
pT(GeV/c)

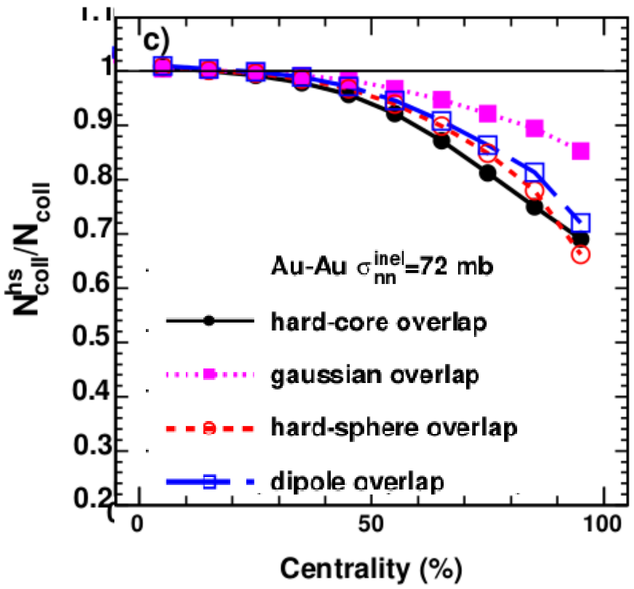
Impact parameter (geometrical) bias

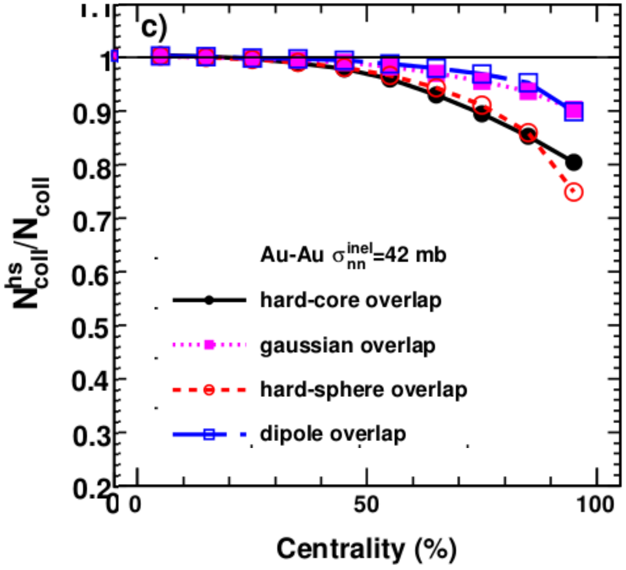
J.Jia, PLB 681 (2009) 320



$$\begin{aligned} T_{AB}(\vec{b}_{AB}) &= \int d\vec{b}_A d\vec{b}_B \; T_A(\vec{b}_A) T_B(\vec{b}_B) t(\vec{b}_{AB} - \vec{b}_A + \vec{b}_B) \\ &= \int d\vec{s} d\vec{b}_{nn} \; T_A(\vec{s}) T_B(\vec{s} - \vec{b}_{AB} + \vec{b}_{nn}) t(\vec{b}_{nn}). \end{aligned}$$

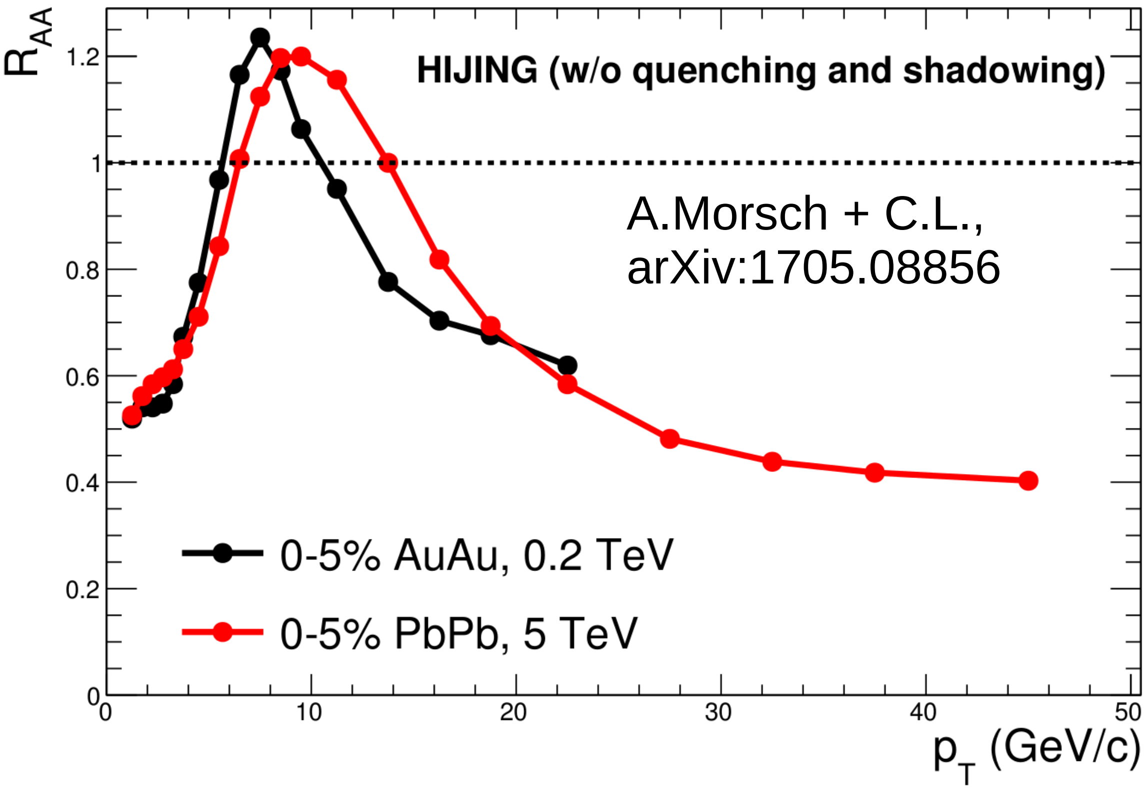
$$N_{\rm coll} = T_{\rm AB}\, \sigma_{\rm NN}$$





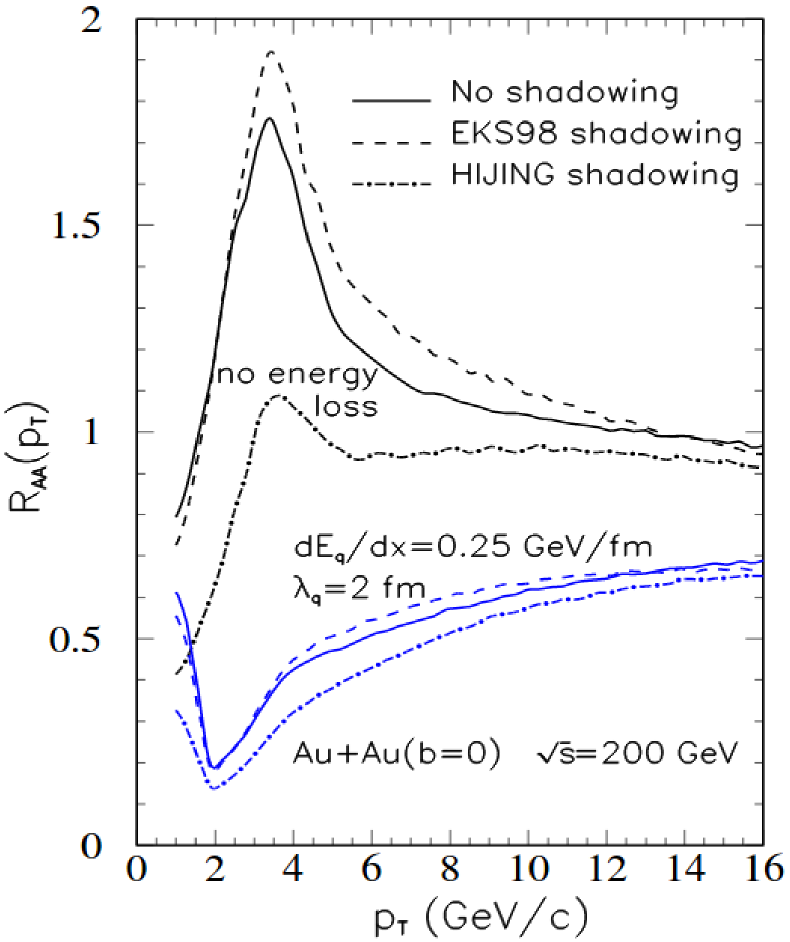
Including a impact parameter dependent nucleon-nucleon overlap function can lead to 20% variation of Ncoll for peripheral collisions

HIJING


HIJING (1.383)

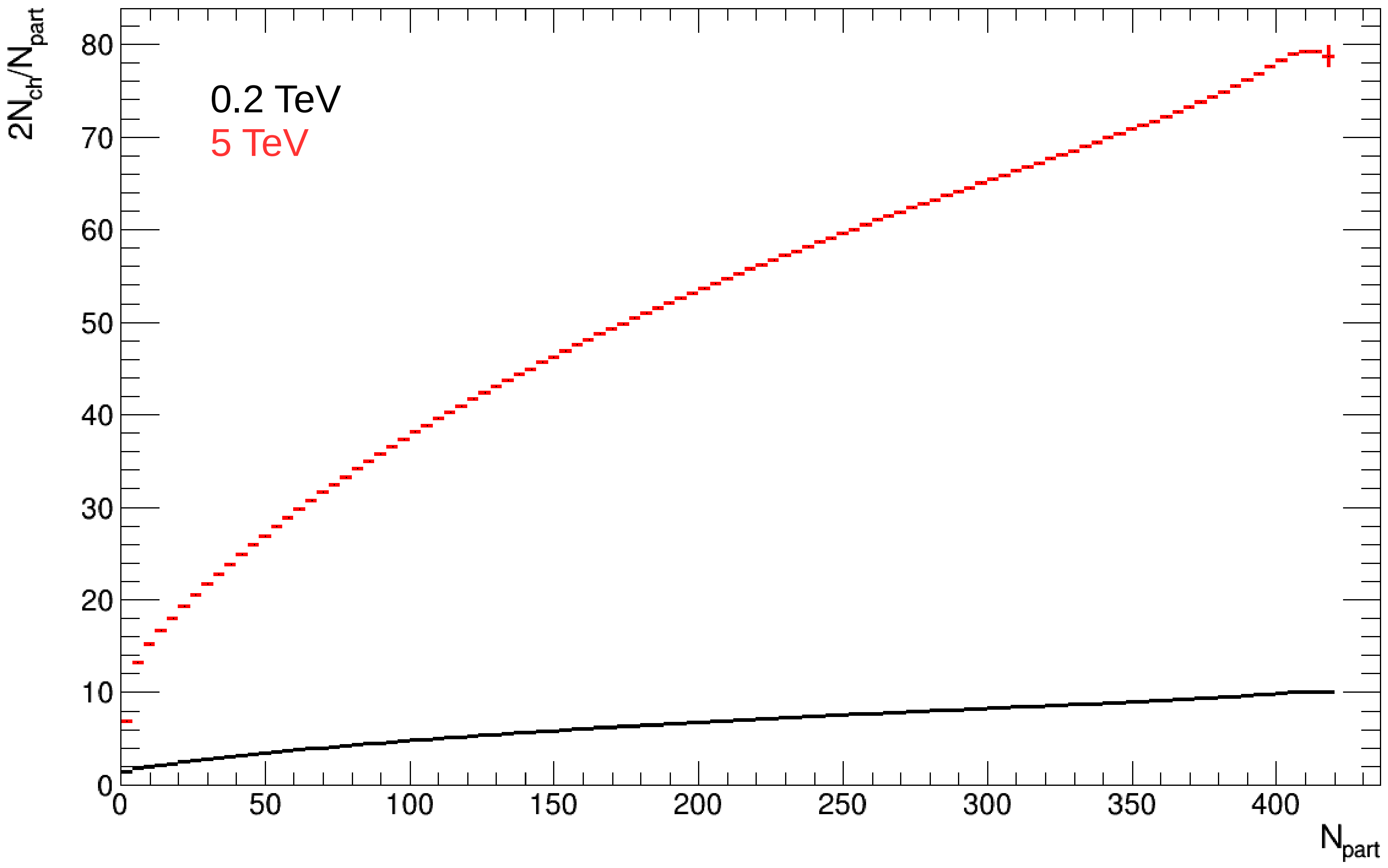
A.Morsch + C.L., arXiv:1705.08856

PRC 61 (2000) 064910



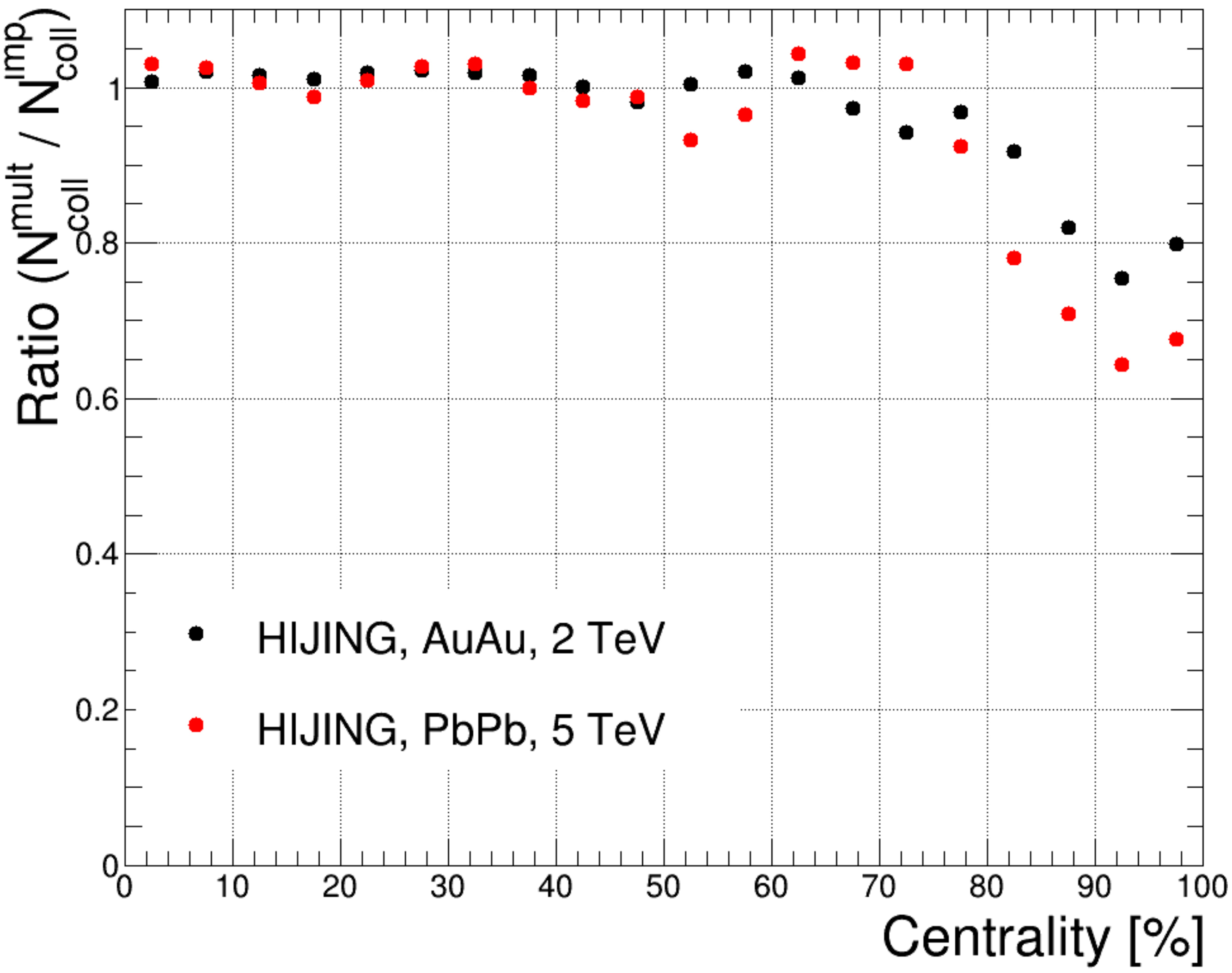
Un-understood features in central PbPb related to adhoc-momentum conservation, multiple scattering, and “error treatement” in HIJING. Does not give RAA→1 at high p_T

HG-Pythia multiplicity dependence



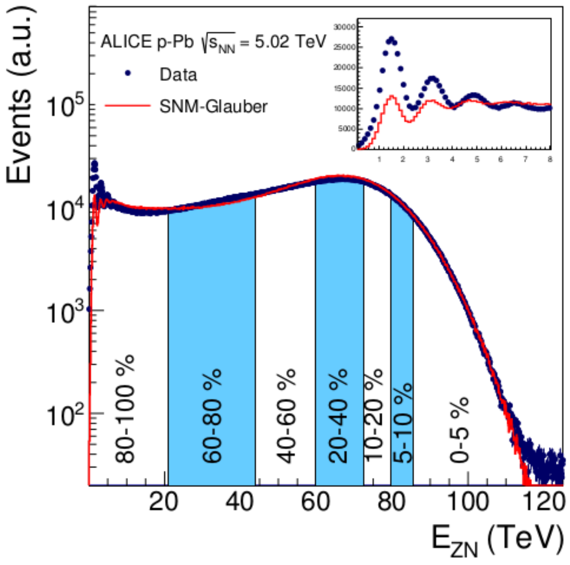
By construction, does not well scale with Npart, but rather with Nhard (or Ncoll)

Use of impact parameter Ncoll



In peripheral collisions, it matters whether one slices Ncoll vs b (called geometric) or using a particle production model (HIJING, Glauber fit)

Centrality from HYBRID method



1) Assume ZN is bias free + define centrality classes
2) Construct similar model as for the Glauber fits

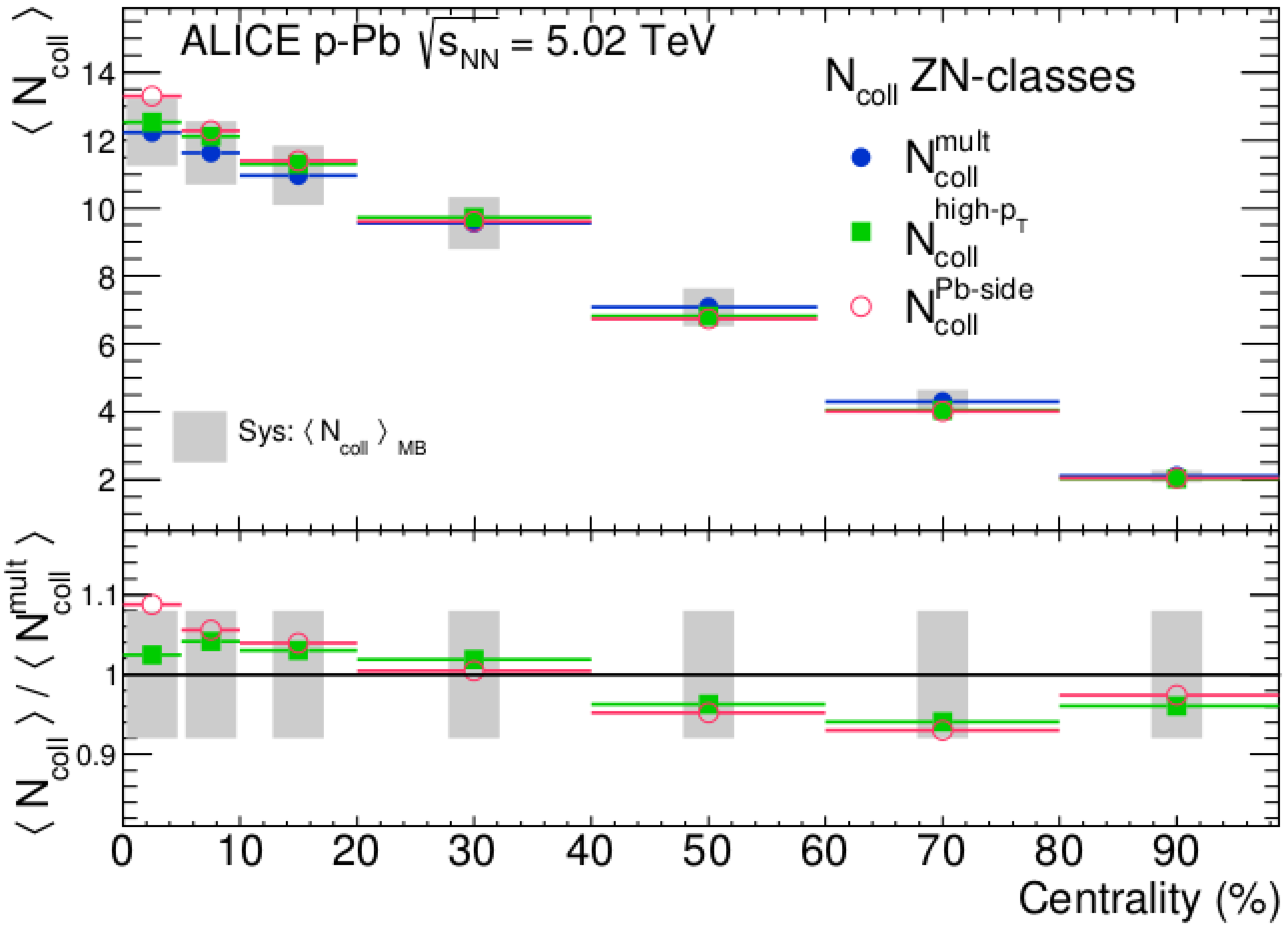
Resulting values within at most 10%

ALICE, PRC 91 (2015) 064905

$$\langle N_{\rm coll}\rangle_i^{\rm mult} = \langle N_{\rm part}\rangle_{\rm MB} \left.\frac{\langle dN/d\eta\rangle_i}{\langle dN/d\eta\rangle_{\rm MB}}\right|_{-1<\eta<0} - 1$$

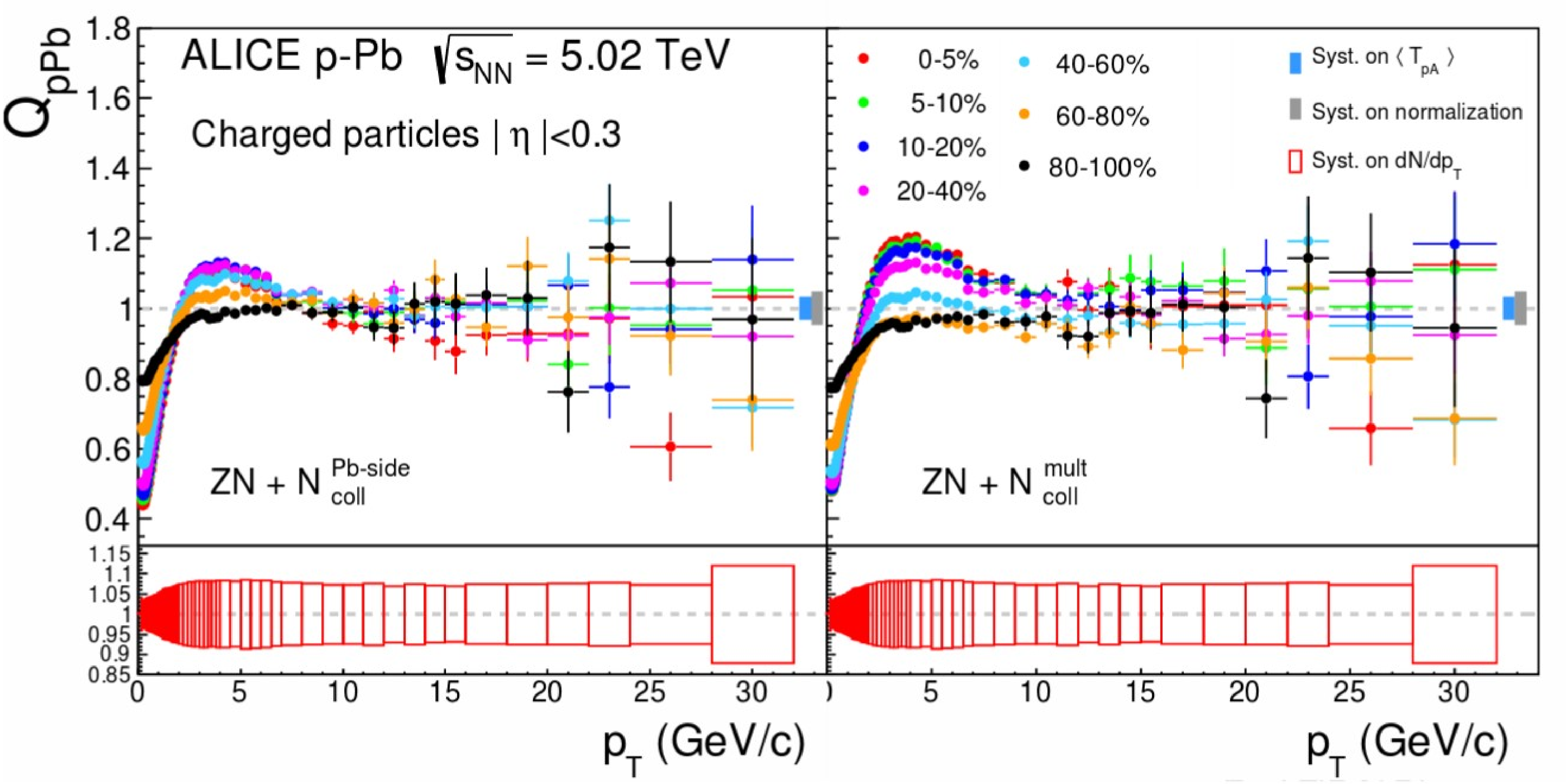
$$\langle N_{\rm coll}\rangle_i^{\rm high\,p_T} = \langle N_{\rm coll}\rangle_{\rm MB} \frac{\langle Y_{10<p_T<20}\rangle_i}{\langle Y_{10<p_T<20}\rangle_{\rm MB}}$$

$$\langle N_{\rm coll}\rangle_i^{\rm Pb\,side} = \langle N_{\rm coll}\rangle_{\rm MB} \frac{\langle S_{\rm V0Ar1}\rangle_i}{\langle S_{\rm V0Ar1}\rangle_{\rm MB}}$$



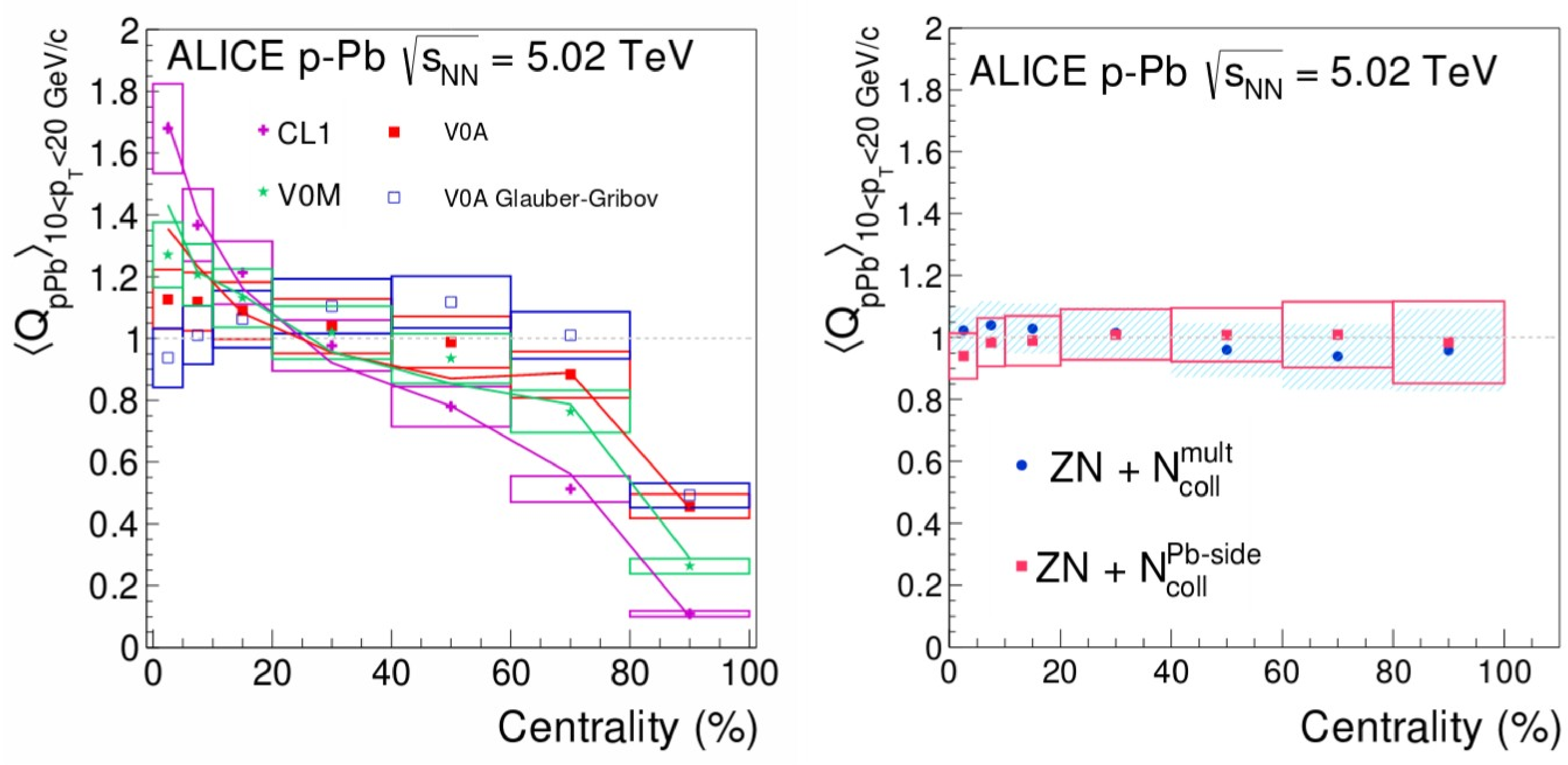
Results using the hybrid method

ALICE, PRC 91 (2015) 064905



Multiplicity vs ZN selection

ALICE, PRC 91 (2015) 064905



ATLAS, PRC 90 (2014) 044906